INTERIOR OF A CONIFEROUS WINDBREAK IN NORTHEASTERN IOWA. WHITE AND RED PINES; THE BELT FLANKED BY WHITE CEDAR AND LARCH.

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HENRY S. GRAVES, Forester.

WINDBREAKS:

THEIR INFLUENCE AND VALUE.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Forest Service,
Washington, D. C., January 5, 1911.

Sir: I have the honor to transmit herewith a manuscript entitled "Windbreaks: Their Influence and Value," by Carlos G. Bates, in charge of experimental work in District 2, and to recommend its publication as Bulletin 86 of the Forest Service.

Respectfully,

Henry S. Graves,
Forester.

Hon. James Wilson,
Secretary of Agriculture.

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WINDBREAKS: THEIR INFLUENCE AND VALUE.

PART I.

A SYNOPSIS OF CONDITIONS.

PURPOSE OF THE STUDY.

When the early settlers in the Middle Western States planted trees so extensively they did so with a distinct object in view—to build up a natural barrier against the winds which then swept unimpeded across the plains, doing immense damage to their crops, intensifying the effects of both hot and cold weather upon their stock, and making their homes almost uninhabitable. The attitude of many of the present-day farmers, however, and especially the younger men who have never experienced the rigors that characterized earlier days, is quite changed. There is a common indifference to timber culture, and although there has been of late years considerable interest throughout the West in commercial plantations, there is no such extensive windbreak planting as formerly. On the contrary, there is a revulsion of feeling; an idea that all but the most productive tracts of planted timber should be done away with and their place taken by crops which will bring quick money returns. The State of Kansas, once the prey of winds, has placed itself on record as opposed to the maintenance of efficient hedge windbreaks along roadsides.[1] There has also been a great deal said to disfavor cottonwood. The general observations upon which these prejudices are based are likely to be misleading, and their inaccuracy and unreliability are convincingly shown by the figures obtained through careful study, which prove that cottonwood is the least damaging of all the hardwood trees in its relation to field crops. Yet the common opinion is that it is the most so.

There is obviously much basis for the belief that forest plantations do not yield as great a revenue from the direct forest products as annual crops would on the same land. The fault, however, lies quite as much with the owners of the timber as with the trees themselves; for, while much progress has been made toward improved and more intensive methods of crop management, little has been done to increase the productiveness of the grove or belt of trees. Occasionally the farmer goes in with an ax to take out a tree for fuel, to obtain a

[1] General Statutes of Kansas, 1901, secs. 3116-3118, provide that all hedge fences along the public highway shall be cut and trimmed to not more than 5 feet high, except when protecting orchards, vineyards, and feed lots. The adoption of this statute is left to popular vote in each county.

barn prop, or a temporary substitute for a wagon tongue, but his methods are wholly destructive, and the condition of the forest plantation goes from bad to worse. The great need is for better management; some care to secure natural reproduction to replace the old trees; underplanting, if necessary, to fill out the stand and to insure a continuous crop; and the exclusion of cattle from young groves. In general, this care has not been given to forest plantations, and, as a result, the revenue from them is only a fraction of what it would be under good management. The Forest Service has already issued a number of publications [1] which show that the revenue to be derived from plantations of forest trees properly selected and managed is considerable. The farmer's main objection is that he can not afford to wait for his income until the trees have matured. When the protective value of timber tracts is rightly considered, however, as will be shown in the following pages, there will be in the benefit to crops, and in other helpful influences of the belt of trees, an annual income of considerable magnitude in addition to the value of thinnings, which, in certain regions, will bring the productiveness of the forest up to that attained by field crops.

The very lack of reliable information concerning the protective value of windbreaks, together with the now common argument that they do more harm than good, makes their study exceedingly important. The present study has been concerned entirely with the collection of data showing the effects of windbreaks upon field crops and with calculations of their net value to the average farm of the Middle West. The economic importance of tree planting in this region can be realized only when it is known that there are, for example, in one township in Harvey County, Kans. (middle eastern), approximately 170 miles of windbreak, mostly single rows of osage orange, with an average height of about 20 feet. In a valley county (Platte) of Nebraska there are in one township approximately 22 miles of rows, belts, and groves, mostly cottonwood, with an area of about 425 acres and an average height of 55 feet. On the uplands in the State (York County) there are in a single township about 40 miles of windbreaks. In Faribault County, Minn., one township contains approximately 400 acres of cottonwood and willow groves.

The Forest Service has conducted experiments to obtain a clear idea of the influences of windbreaks upon the atmospheric and soil conditions which affect the growth of plants. These influences known, it is but a step to apply these general principles to local conditions and to determine the relative values of various species and of various arrangements of windbreaks with respect to local winds, and their positive value to certain crops.

[1] Miller: Forest Planting in Eastern Nebraska, Cir. 45; Forest Planting in the North Platte and South Platte Valleys, Cir. 109. Kellogg: Forest Planting in Western Kansas, Cir. 161; Forest Planting in Illinois, Cir. 81 Fetherholf: Forest Planting on the Northern Prairies, Cir. 145. Baker: Native and Planted Timber of Iowa, Cir. 154.

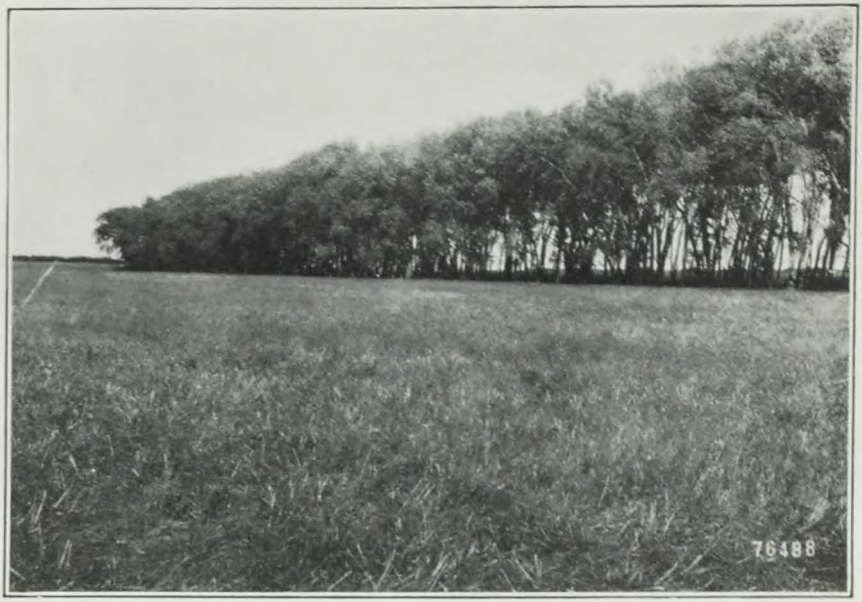

FIG. 1.—COTTONWOOD IS PREEMINENTLY THE TREE OF SANDY BOTTOM LANDS IN THE MIDDLE WEST.

FIG. 2.—BELTS OF SILVER MAPLE AND OTHER SPECIES ADD TO THE BEAUTY AND VALUE OF THE RIVER BOTTOM FARMS. PLATTE COUNTY, NEBR.

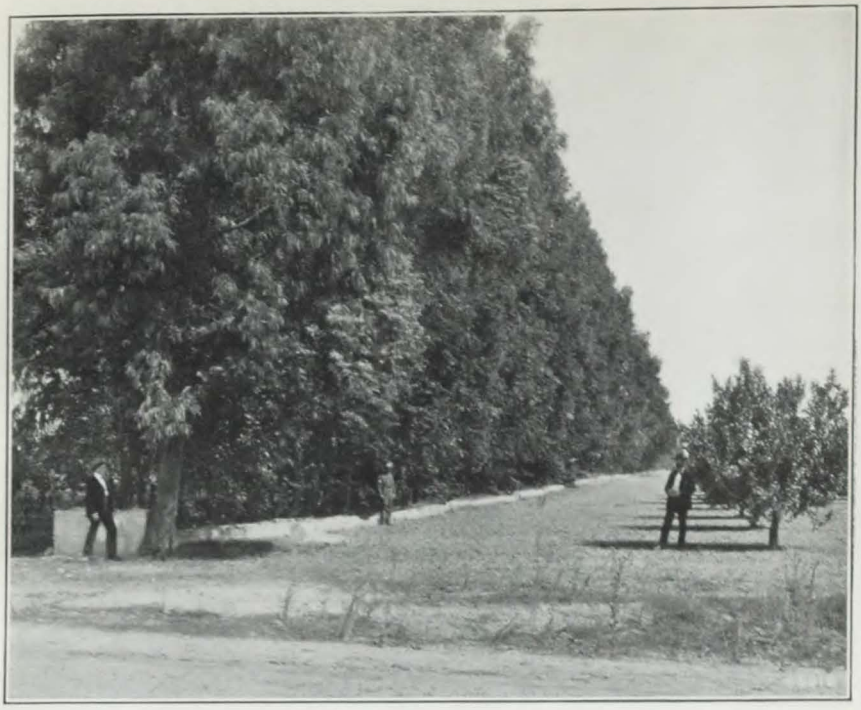

FIG. 1.—NARROW BELTS OF EUCALYPTS ARE PLANTED ABOUT THE ORANGE ORCHARDS OF CALIFORNIA.

FIG. 2.—ON IRRIGATED LANDS IN EASTERN COLORADO (MESA COUNTY) THE LOMBARDY POPLAR, A CLOSE RELATIVE OF THE COTTONWOOD, GROWS THRIFTILY, AND IS USED FOR THE PROTECTION OF ORCHARDS.

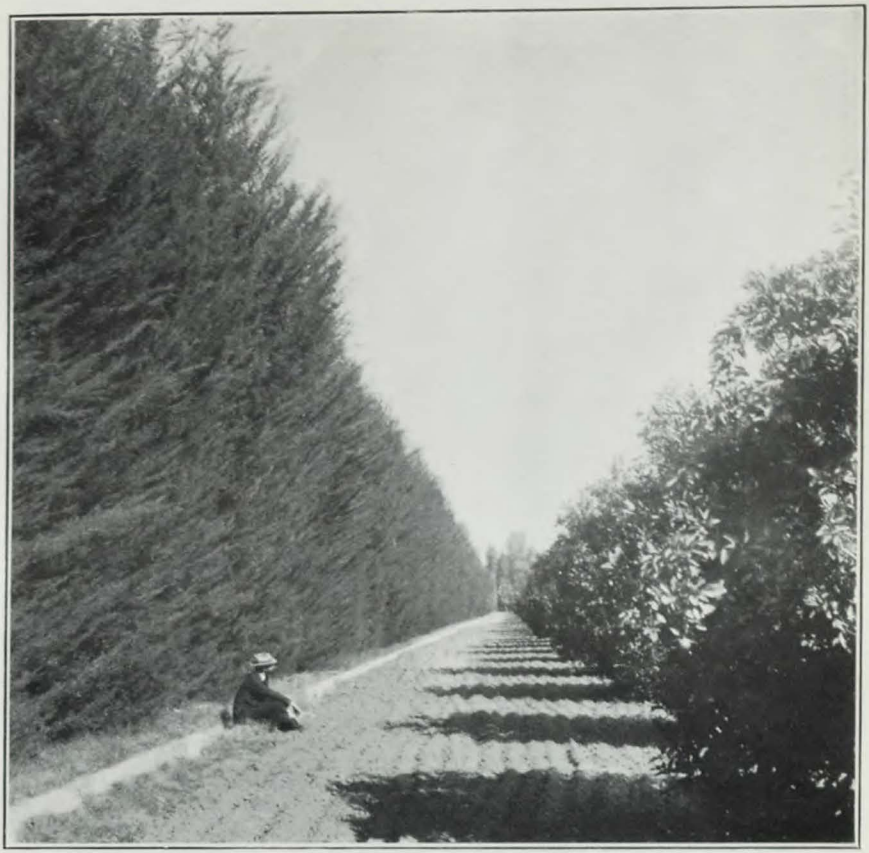

FIG. 1.—THE MONTEREY CYPRESS IN CALIFORNIA MAKES AN EXCELLENT WINDBREAK FOR THE PROTECTION OF CITRUS ORCHARDS.

FIG. 2.—DENSE GROVES OF EUCALYPTS PROTECT FIELDS AND ORCHARDS FROM THE SANTA ANA WIND IN CALIFORNIA.

FIG. 1.—WHITE CEDAR AND EUROPEAN LARCH ARE TYPICAL OF THE LAKE STATES AND THE EAST.

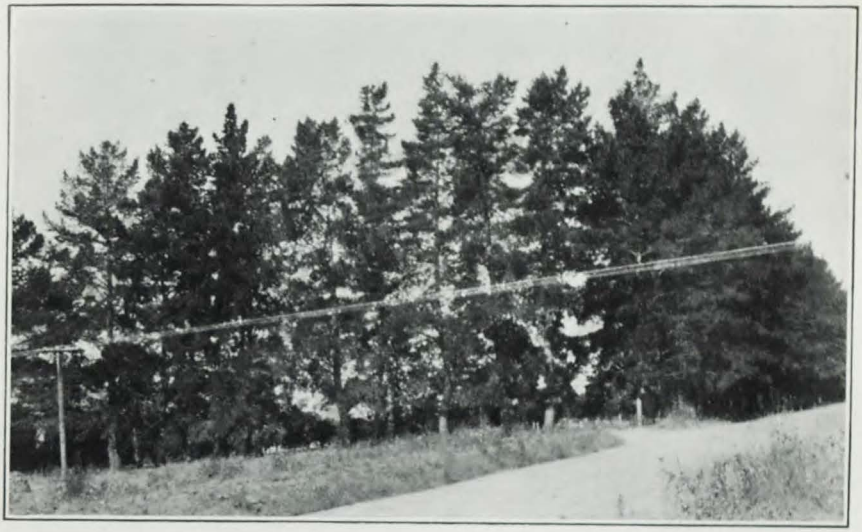

FIG. 2.—MONTEREY PINE IS THRIFTY AND FORMS AN EFFICIENT WINDBREAK.

The work of Prof. King,[1] in determining the effect of a windbreak upon the evaporative power of the wind, and that of Prof. Card,[2] in evaporation, measurement of soil moisture, and effect of windbreak protection on a crop of millet, have been highly suggestive in carrying out the study.

Since the need for windbreaks on the treeless plains of the Middle West is exceptionally great, and since a large number of windbreaks are there available for study within a comparatively small area, the States of Kansas and Nebraska were chosen as the chief field, though studies were carried on in southern Minnesota and in Iowa as well. The results were obtained in a plains country, in which differences of topography do not figure prominently. The necessity of eliminating from the experiments the factors of slope and aspect will be plainly seen in the following discussions.

IMPORTANT WINDS OF THE UNITED STATES.

There is scarcely any part of the United States which is not swept by winds capable of doing serious injury to homes, cattle, orchards, or fields. The winds which do the greatest damage and from which protection is needed are (see diagram 1):

(1) The sea breezes of the Atlantic coast and of the Great Lakes. These may throw up sand dunes along the coast and affect orchards and tender crops by reducing temperatures. They are sometimes augmented by coastal winds resulting from West Indian storms.

(2) The anticyclonic, dry winds of the upper Mississippi Valley and the western Lake region, which, especially in the spring and early summer, often blow steadily from the west or southwest for several days.

(3) Anticyclonic winds of the central and southern portion of the Mississippi Valley, usually from the southwest, but more or less influenced in summer by the general continental winds from the southeast and in winter by winds from the north. These also are often very persistent in summer and are exceedingly dry when blowing off the plains of the Southwest. The northwest winter winds of the entire Mississippi Valley are usually very cold and dry, and are likely to injure vegetation.

(4) The Chinook, which blows out of the northern Rocky Mountains, increasing in warmth and dryness with its descent, and, in the Canadian Provinces, Montana, and the Dakotas, doing great damage by prematurely accelerating plant growth, which later may be subjected to extreme cold.

(5) The Santa Ana, or desiccating north wind of southern California, which blows from the Mohave Desert, and similar winds on the coasts of Washington and Oregon which blow from the high plains, are often destructive to vegetation by reason of their dryness.

[1] Bull. 42, Wis. Agr. Exp. Sta. [2] Bull. 48, Nebr. Agr. Exp. Sta.

(6) The sea breezes of the Pacific coast, usually very moderate. In summer, however, their warmth enables them to take a great deal of moisture from fields and orchards.

The economic value of windbreaks is controlled not only by the prevalence of damaging winds in a region, but also by climatic factors which affect the growth of the trees themselves, and hence the productiveness of the windbreak as a forest unit. Although windbreaks are useful and add to the comfort of living, to plant them on an extensive scale for the protection of large areas can be recommended only where their combined protective and timber value is equal to the value of field crops which might be grown on the same area. The relative value of the direct and indirect benefits of timber

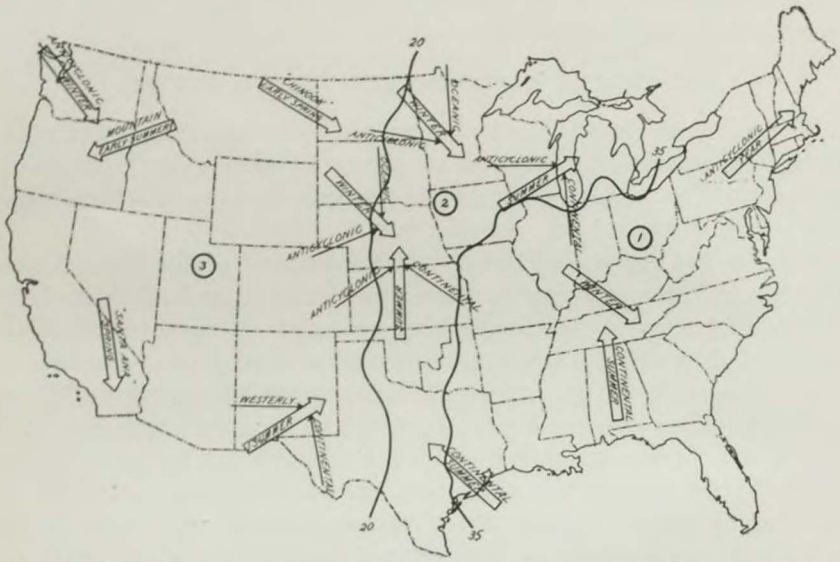

DIAGRAM 1.—Direction, origin, and season of winds injurious to agriculture. Lines of equal rainfall controlling the use of windbreaks. 1—Windbreaks for timber production, and special protection. 2—Windbreaks for timber production, and general protection. 3—Windbreaks for general protection, little timber value.

units is determined by the moisture conditions of the climate. From this standpoint the area of the United States may be divided into three belts (see diagram 1):

(1) In the plains region east of the Missouri River, even though winds are prevalent at certain seasons and the level topography permits their free sweep across the fields, the abundant rainfall (30 inches at Omaha, Nebr., to 35 inches in northern Illinois) and generally high humidity of the air greatly decrease evaporation and its bad effects upon plants. The small value of windbreaks as protection to crops, or even their positively injurious influence surrounding land where drainage is poor, makes it necessary that they should be sufficiently compact and well managed to yield timber of a value

comparable to that of field crops. For special purposes, however, such as the protection of valuable orchards and the shelter of homes, the utility of the windbreak may be so great that its timber value need not be considered. In most of the eastern half of the United States the farmer's woodlot will generally take the place of rows or narrow belts. Perhaps occupying a site not suited to cultivation, it will yield a good revenue from its crop of valuable hardwoods.

(2) In regions with less than 30 inches of annual precipitation the conservation of moisture becomes so important that in open level country windbreaks are extremely valuable for the protection of fields, pastures, and meadows. This is also true in the more rolling lands of the South, where, even with greater precipitation, the constantly high temperature during the growing season accelerates evaporation. From Texas and Oklahoma to Kansas, Nebraska, and South Dakota, hot southerly winds, with a remarkable capacity for moisture, prevail throughout the growing season, and in years with less than the normal rainfall they have done immense damage. The past few years, however, have witnessed very little damage, and there has grown up the feeling that the climate of the region has permanently changed both by a decrease in winds and an increase in the rainfall. Records of the Weather Bureau for several of the stations west of the Missouri River, however, show that the recent group of wet years corresponds to a similar group about 1880, with dry years in the early nineties. There has been no permanent change in the climate, and there is good reason to believe that a series of dry years will follow the present period of abundant moisture. The records of wind movement at several stations, for the same period, show a slight decrease in the last 15 years as compared with the preceding 15, and it seems likely that if the observations of the Weather Bureau had been made near the ground rather than at the tops of buildings an even greater difference would have been noted. It would be strange, indeed, if the thousands of barriers which have grown up where formerly no trees existed had had no general effect in reducing the velocity of surface air currents. However, there has been no change in the universal conditions which cause general winds, and the removal of the objects which have locally broken them will quickly and certainly bring about a return to original conditions.

In the northern part of the Mississippi Valley, from the prairies of Montana to the Dakotas and Minnesota, and even in northern Indiana and Michigan, the anticyclonic winds of summer may blow very persistently, and while frequently injurious to grain, hay, and other crops, the cooler and moister quality of the air reduces their damaging capacity, and little provision has been made to check them. In this northern region, from eastern Washington to the Lakes, the northerly blasts of winter and the spasmodic Chinook wind of spring

are considered more serious. Even in this latitude the protective value of windbreaks properly placed would warrant their more extensive use.

In that portion of the plains region where the rainfall exceeds 20 inches tree culture has been most developed, and results show that a fair profit may be expected from the timber yield of the best adapted species. Here, therefore, the windbreak serves a double purpose—protection and production. Since the production is not comparable to that of field crops, however, and since the protection may be unnecessary in certain years, both must be considered.

(3) Where there is less than 20 inches of rainfall per annum, especially in the southern portion of the plains, every drop of moisture is of value to crops, and its conservation becomes of the utmost importance. In this region "dry farming" and irrigation are being widely developed, and the checking of evaporation can not fail to be of great benefit. Little has been done in windbreak planting, but it is certain that the benefits obtained in more humid regions can be had here in even greater degree. In such regions as eastern Colorado, western Oklahoma, Texas, and New Mexico, even though the difficulty of establishing windbreaks is great and their timber value small, they will prove profitable through their effect on the conservation of moisture. In New Mexico, low, shrubby species like sage-brush have been used with thorough success.

THE UTILITY OF WINDBREAKS.

The term "windbreak" may be applied to any object which serves as an obstacle to surface winds. For the purposes of this study, however, it must be limited to bodies or rows of trees. Windbreaks may be divided according to their general arrangement into three classes: (1) Rows and hedgerows; (2) belts or shelter belts; (3) groves, or, in the most extensive case, forests. A belt usually consists of three rows or more, but its width is less than twice the ultimate height of the trees.

In European countries the windbreak perhaps serves its greatest utility as a check upon drifting sands along the coast, especially in France. In the interior steppes of Russia, which correspond to our middle western plains, windbreaks have been planted more or less extensively to protect fields from the desiccating winds of the region. In Schleswig-Holstein earth walls are thrown up and shrubbery is planted upon them, since forest trees can not be made to grow there.

Although windbreaks are of very real benefit to the famer and fruit grower everywhere, it is in the treeless, wind-swept plains that they find their greatest utility. In addition to the esthetic benefits and the general "improvement" value to the farm, it would in many instances be almost impossible to raise crops without protection from the hot, dry winds of summer and the cold, dry winter winds.

The early settlers realized the value of trees for protection and attained success in tree planting under conditions which at first seemed very unfavorable. First, small groves were planted about the houses and barnyards. Gradually these were extended in the form of belts or single rows to protect the larger areas of orchards and fields. Where the soil was light it was necessary to prevent its drifting. The farmers soon found also that a windbreak was very useful in preventing the drifting of snow. Railroad companies made many desultory attempts to protect their tracks by planting belts of trees far enough away to serve as snow traps, but more frequently loose fences were used.

Orchards must be protected from the mechanical effects of the winds which strike the trees when they are laden with fruit; from their drying effect, which blights the fruit and causes it to shrink; and from the drying or "winterkilling" of the branches. This applies not only to the prairie States but also to the lake States, the fruit region of California, and the Columbia River Valley fruit region. In many sections of Michigan, Wisconsin, Illinois, Maine, and New York, where peach growing was formerly profitable, it is now impossible to raise consistent crops of this fruit because of the increased exposure that has resulted from the removal of the original forests.

It is necessary to consider also such winter crops as wheat and rye. For the protection of these the windbreak serves the double purpose of causing an even distribution of the protective snow cover and of sheltering the tender plants from the wind itself, once the snow has melted. The protection of all summer crops is important.

The protection of stock is a matter of no small importance in many of the Western States, where there are large ranches with no more adequate shelter for the cattle than that afforded by a grove of trees. Instances have been recorded where large herds of cattle have passed through a severe winter in the shelter of a cottonwood grove. Such a condition represents a low state of development in the economy of the stock business, but the usefulness of a windbreak for the protection of sheds and winter yards may always be considered.

HOW WINDBREAKS ACT.

A windbreak may affect crops or other objects near it only through the agency of the atmosphere or soil. It may furnish protection to man or beast or plant growth only by the interception of air currents and the consequent effect upon wind velocities and air temperatures. It may have both beneficial and detrimental effects upon field crops. In the narrow zone adjacent to a row of trees or to the edge of a grove, the effect of the trees upon field crops is that which results from a vigorous competition between the two classes of plants for the essential elements of growth—sunlight and soil moisture. By the inter-

ception of air currents over a much wider zone the windbreak may influence the growth of crops and usually the influence is for good. It reduces the mechanical force of the wind; it lessens evaporation, which is always accelerated by air currents; it stagnates the air and thus increases the extremes of temperature both in the air and in the soil; and, finally, it changes the distribution of the moisture of the air.

The constant aim throughout this study has been to painstakingly investigate the influences of both classes, and to determine to what extent the baneful effect of the trees might be reduced without destroying the ability of the windbreak to protect. The studies of physical factors in the zone near the trees were made to determine the requirements, with respect to soil moisture and sunlight, of the species which have proved successful in windbreak planting and to show how the space occupied by the trees may best be utilized to increase its yield without damage to the crops adjacent. The study of the more distant relations of windbreaks was made to determine under what conditions and to what extent benefit may be expected from the protection afforded; to show whether the aggregate benefits from protection alone will warrant the existence of the windbreak.

SYSTEM OF MEASURING INFLUENCES.

The general system of study has been to measure and compare the conditions existing under and near the trees with conditions for the same period at a point far enough removed from the trees to be beyond their influence. It was impossible to study simultaneously the various classes of windbreaks in various localities, but care was taken, in making comparisons between different species and different windbreak formations, to consider all essential points.

In calculating the effect of a windbreak upon crops a given area must be allotted to the trees, and the study of effects must be carried on outside of this area. In the case of groves the area belonging to the trees themselves has been considered to be that lying between the outside rows, measuring from trunk to trunk. A belt of trees or a grove thus occupies a definite space, and measurements of distances in either direction from this area are made from the trunks of the outside rows. A single row of trees can not be said, in this sense, to occupy any space. Measurements of distances in both directions are made from a common point on the line of the row. By this system it is possible to compare directly the influence of the different classes of windbreaks in the zone affected by the roots and branches and in the wider outlying zones protected by the trees without considering the area which belongs strictly to them.

Since the yield of a field of grain depends so much on the methods of cultivation and local soil conditions, an attempt has been made in measuring the effect of each windbreak to determine a normal,

local yield for each field concerned and to express other local quantities as a percentage of this yield, rather than to compare different fields by absolute yield. In the case of corn crops the normal yield of each field has been determined at a point far enough from the windbreak to be beyond its influence. For two fields on opposite sides of the same windbreak two normals must be determined.

In measuring the effect of windbreaks upon orchard crops comparisons have been made only between protected and unprotected orchards and no attempt has been made to determine a normal yield for each orchard. The orchards studied were all in the same general region and were affected by the same soil and climatic conditions, so that their chances of producing crops in the season of 1908 were equal except as the yield was affected by the presence or absence of windbreaks.

Other things being equal, the influence of a windbreak is proportional to its height; and as height increases so also the width of branching increases, the shadows extend, and the roots grow and extend in one direction or another. In order to make the measurements under all conditions directly comparable, the height of the trees in any windbreak has been taken as the unit of measurement and horizontal distances have been expressed in terms of this unit. Thus, the terms "1-ht.," "5-ht.," "10-ht." indicate distances in terms of tree height, as equal to the height of the trees, five times their height, or ten times, as the case may be. The extent of branches or roots actually measured in feet is everywhere expressed in the form of percentages of the height of the trees. Thus, the average height of a row of cottonwoods may be 50 feet and the average horizontal distance from the trunks of the trees to the ends of their branches on a given side may be 25 feet. The branching will therefore be expressed as 0.50-ht., meaning 50 per cent of the tree height. Similarly, it may be found that the roots of the trees extend 30 feet on a given side and this will be expressed as 0.60-ht. Again it may be found that the windbreak has an appreciable effect upon wind velocity out to 500 feet from the base of the trees, this distance being expressed as 10-ht., and the greatest yield in the field adjacent to this windbreak may be found at a distance of 200 feet, this being expressed as 4-ht.

In considering areas which may be influenced by a windbreak it is assumed that the quantities determined at any point along the axis of the windbreak represent an average for the entire length of the windbreak. It is, therefore, unnecessary to consider the length of the windbreak or the length of the field adjacent to it, and instead of calculating areas on the basis of acreage or square feet, they are considered to be of indefinite length and of a width which bears a definite relation to the height of the trees. The acreage involved in any case may be directly calculated if the length of the windbreak is known.

PART II.

MEASUREMENTS OF PHYSICAL FACTORS—PHYSIOLOGICAL EFFECTS UPON PLANTS AND ANIMALS—CROP YIELDS.

METHOD OF MEASURING FACTORS.

Before describing the influences of windbreaks through the agency of physical factors a brief description of the methods employed in measuring these factors will help toward an understanding of results. The amount of competition for sunlight and soil moisture has been measured; the atmospheric conditions which affect crops at some distance from the trees have been studied; and the various influences have been segregated and expressed quantitatively. This work comes within the province of plant physiology, and the methods used are those known to plant ecologists.

SUNLIGHT.

Of all the factors in the competition between trees and smaller forms of vegetation, sunlight is of the greatest importance, since the large stem and branches and the immense mass of foliage in a tree crown gives the tree a certain advantage over smaller plants.

The object in measuring quantities of light in connection with this study of windbreaks is to determine what damage may result to crops from the interception of light rays by the crowns of the trees. Since various trees *use* different amounts of light and since the several crop plants *require* different amounts, much may be gained by a study of the light conditions in the areas occupied by different kinds of windbreaks and by the study of the crops upon which they may have an influence.

The total shading effect of a row of trees is obtained by measuring the extent and intensity of the shadow for each hour of the day. The amount of direct sunlight which passes through the crowns of the trees at any point and time is measured by exposing a strip of solio paper for a given period, under the given light conditions, and by comparing the shade of color thus produced with the shade obtained by a similar exposure in full sunlight. Such exposures are made at intervals of 10 feet on either side of the windbreak and as far as the shadow extends at the time. The amount of light in the shaded area is expressed as a percentage of the full sunlight for that particular hour, and in calculating the total amount of light which reaches a given point in all of the hours between sunrise and sunset, each percentage is reduced in the proportion of the value of the hourly direct

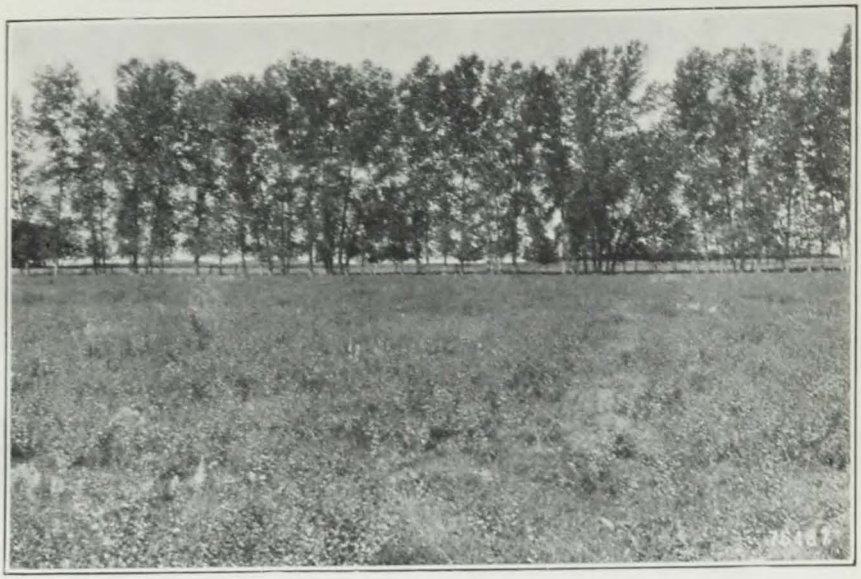

FIG. 1.—A NORTH-SOUTH ROW HAS THE ADVANTAGE OF GETTING LIGHT FROM THE SIDES; DENSE BRANCHING, ALMOST TO THE GROUND.

FIG. 2.—AN EAST-WEST ROW RECEIVES LIGHT ONLY FROM ABOVE; LOWER BRANCHES SHADED OFF.

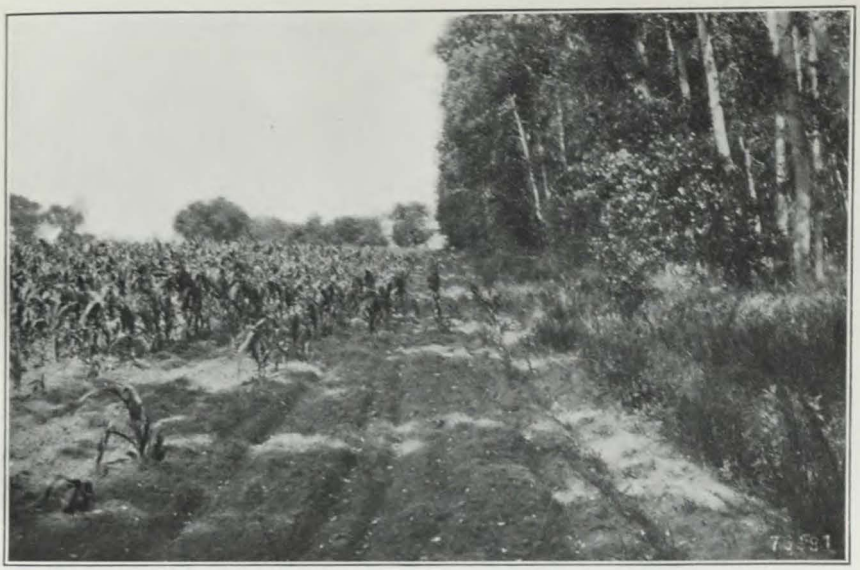

FIG. 1.—CORN TO THE NORTH OF A COTTONWOOD GROVE IS BADLY DAMAGED BY SHADE IN A FEW ROWS ADJACENT TO THE TREES.

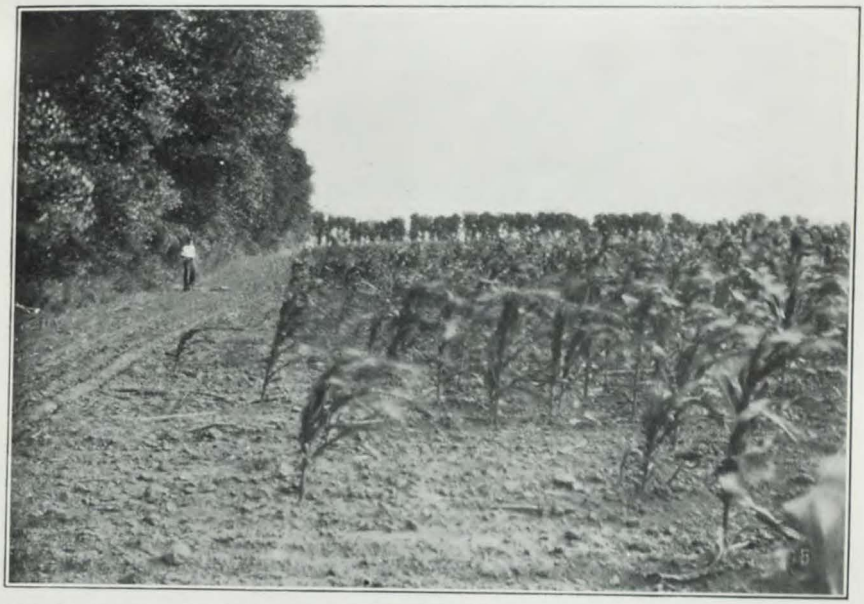

FIG. 2.—ON THE EAST OF COTTONWOOD THE SHADING EFFECT IS NOT SO MARKED, BUT IS FELT OVER A WIDE AREA.

sunlight compared with that at noon. Thus, for example, light at 8 a. m. or 5 p. m. may be valued at only 25 per cent. Hence, the shading of a given point at noon means a greater loss than the same shade thrown on the point in the early morning or late afternoon. For the purpose of comparing different species under different conditions, the amount of light used by a given windbreak is expressed as a percentage of the total light which would fall during the entire day on a strip of ground parallel to the windbreak and as wide as the height of the trees.

A row of trees may use 75 per cent of the light which would naturally fall upon the strip of ground 50 feet wide contiguous to the trees, and in the 50 feet next outside of this the shadow may represent the use of only 25 per cent of the light. If this lesser shadow were combined with the greater and concentrated on the first strip, it might then be said that the shading is equal to 100 per cent of the light which would fall upon a strip of ground 50 feet wide. If, then, the height of the windbreak is 50 feet, the shading amounts to 100 per cent of a strip of ground whose width is 1-ht. If, however, the height of the trees in this case is only 25 feet, the amount of light used amounts to all of that which would fall upon a strip of ground whose width is 2-ht., or 200 per cent of the light on a 1-ht. strip. By this system, in comparing different windbreaks, the element of tree height may be eliminated. It may be seen that this figure which expresses the quantity of the shade produced by the windbreak may be more than 100 per cent.

SOIL MOISTURE.

The relation of trees to crops in their competition for soil moisture is decidedly important. The tree roots reduce soil moisture adjacent to windbreaks, and this effect is usually apparent in the yield of the crop growing there. A special effort has been made to determine the *root extent* of the various species which are used for windbreaks in order to decide which are least likely to damage crops extensively in seasons when the rainfall is not sufficient for both trees and crops. Just as trees vary in the vigor of their stem and crown growth, they show varying root vigor. Even the so-called taproot species have some lateral roots in the well-aerated soil not far below the surface. These are the ones which compete with the cultivated plants for moisture, and the greater their length, the greater the possible damage to crops.

To determine the extent of the tree roots of various species, a number of soil samples, taken at regular intervals out from the base of the trees, show to what extent, as expressed in distance and in moisture percentages, the roots have an appreciable effect in depleting the moisture supply of the soil. The samples are taken at depths of

10 and 20 inches or more, and at intervals of 10 or 20 feet on both sides of the trees, giving for each windbreak a complete soil survey. The amount of moisture found in any soil sample is expressed as a percentage of the dry weight of that sample. Having determined the normal moisture per cent for a given field at the given depth, it is only a step to locate by graphic methods the point at some distance from the trees at which the activity of the roots ceases. This distance, which may be from one-half to three times as great as the height of the tree, is expressed as a percentage of that height.

MECHANICAL FORCE OF WIND.

The windbreak directly reduces the mechanical force of winds and through this reduction has several other influences. The measurement of velocity of surface air currents has been carried on chiefly in connection with studies of evaporation and is accomplished by the use of the standard anemometer, which expresses the wind velocity in miles per hour. As in the case of all other atmospheric measurements in this study, the anemometer is set up at a height of 4 feet from the ground. One instrument, in a fully-exposed situation gives the normal wind velocity for a stated period, while at the same time other instruments exposed at certain points within the area influenced by the windbreak show comparable velocities. The distances from the windbreak are always even multiples of the height of the windbreak.

EVAPORATION.

The ability of the windbreak to check evaporation must be its source of greatest benefit, since, in the region where windbreaks find their greatest usefulness moisture is almost always insufficient for the best interests of agriculture. To thoroughly understand the influence of a windbreak upon evaporation it should be stated that the evaporation of water from any wet surface and also the transpiration of moisture from the leaves of plants is accelerated by three conditions—heat, dryness of the air, and rapid air circulation. Hence, anything which reduces the movement of the air reduces the rate of evaporation and may effect an appreciable saving of the moisture supply.

Evaporation has been measured in a way which shows about the same effects of windbreak protection as are felt by the plants of a field crop. In other words, the evaporating surface of the instrument responds to the same influences as do the leaves of plants. The evaporometer consists of a circular sheet of filter paper resting on a thin glass plate and continually moistened by a supply of water which is fed onto the center of the paper. The moist paper is exposed to sunlight, and the circulation of the air above it is

perfectly free, so that it responds readily to changes of temperature and to changes in wind velocity.

In this case, as in measuring wind, the normal evaporation for the period in question has always been obtained by exposing an evaporometer at a point where it could not be affected by the windbreak. Other evaporometers were similarly exposed on both sides of the windbreak at distances from the windbreak which were one, two, and five times its height, and, in addition, on the leeward side at ten and twenty times the tree height. These distances practically cover the entire range of the windbreak's influence upon evaporation. The instruments show the quantity of water evaporated, and the amount evaporated in the open is taken as the normal, or 100 per cent. Amounts evaporated at other points are reduced to percentages of the normal.

HEAT.

While the windbreak affects evaporation by checking the movement of the surface air currents, it may also affect the temperature of the air.

A body of trees modifies the temperature of the air within it. In the daytime direct insolation is prevented and the air is cooler than it is outside. At night the heat waves radiated from the ground are intercepted and the air under the trees is warmer than outside. Comparative uniformity of temperature is further secured by the fact that the boles and branches of the trees store certain quantities of heat and that this heat is only very slowly radiated. These effects of forest cover are, however, confined to the forested area and its immediate neighborhood. Windbreaks are much more important for their effects at a distance. The following general principles should be borne in mind in considering what effects windbreaks may have upon temperatures and in comprehending the methods used to measure these effects:

(1) The earth is warmed daily by insolation and the heat so received is dissipated very soon after the heat of the sun is withdrawn.

(2) The lower strata of soil are heated by conduction of the warmth from above. Conduction is increased by a moderate amount of moisture in the soil, yet evaporation of moisture may reduce the surface temperature and thus reduce also the amount of heat to be conducted downward.

(3) The air is heated only very slightly by the rays of the sun passing through it. As it comes in contact with warm or cold objects, however, it is heated or cooled. By convection or circulation of the air thus heated or cooled there is a constant tendency to reestablish uniformity of air temperature.

(4) The air is heated or cooled in direct proportion to the length of time that it remains in contact with warmer or colder objects, or, in other words, in inverse proportion to its rate of movement over such objects.

(5) The air moves in a horizontal direction over the ground unless so heated and expanded that it is caused to rise. At night there is very little vertical movement of the air currents, but when their horizontal movement is rapid there is a constant mixing of the upper and lower strata of air.

When the earth is radiating heat any object which, like a windbreak, checks air currents raises the temperature of the surface layers of air by increasing the length of their contact with the soil. The presence of this warm blanket of air over the ground increases in turn the temperature of the soil. In like manner a windbreak cools the air by holding it in contact with the ground when late at night or in cloudy weather the earth has practically ceased to radiate heat. Such arrest of air currents, commonly called "stagnation," is known to have an appreciable influence on day temperatures and on the liability to frosts at night. Its effects may be felt by anyone who passes quickly into the zone protected by a windbreak, where in the daytime the air feels more sultry and at night more chilly than in the open.

These influences of windbreaks upon temperatures have been studied by means of simple thermometers located with respect to the windbreak as were the evaporometers. In every case the normal temperature was obtained outside the windbreak's zone of influence, but in other respects the control thermometer has been exposed to the same local influences as were the thermometers on both sides of the windbreak.

To measure air temperatures during the day, thermometers at 4 feet above the ground were read at each hour between sunrise and sunset. At night the minimum temperature at the same points was obtained by a minimum-registering thermometer. Soil temperatures were obtained at the same points by inserting a very delicate thermometer into a small hole bored to a depth of 1 or 2 feet and kept covered between successive readings.

HUMIDITY.

It has been assumed that the greatest effect of a windbreak upon the humidity of the air over grain fields arises not so much from the possibility of the trees adding to or detracting from the moisture content of the air as from their disturbing influence upon the movement and direction of air currents. To determine how great this effect might be the amount of moisture in the air at several points on both sides of the windbreak and at a height of 4 feet from the ground was

determined in a single case by numerous and successive readings of the ordinary cog-psychrometer. The amount of moisture in the air is determined by this instrument and by the use of tables which show the absolute and relative humidity corresponding to any simultaneous readings of the wet and dry bulbs of the psychrometer.

RESULTS OF MEASUREMENTS.

The pages immediately preceding have been given up to a discussion of the methods and principles involved in the measurement of the physical and physiological effects of windbreak. This information is for the benefit of those who may be somewhat unfamiliar with work of the character undertaken in this study. The next succeeding pages take up the results obtained and the conclusions which may be drawn from a careful analysis of the effects of windbreaks on each factor which influences plant growth.

I. LIGHT—EFFECTS OF SHADING.

Complete sunlight surveys have been made in the areas adjacent to a number of windbreaks in order to determine the density of the shade cast by different species and the aggregate amount of light required by different windbreaks. The aggregate amount of light used by a windbreak bears a close relation to the amount of damage which results from its presence along the edge of a field.

The amount of shade cast by any tree in a windbreak, or, in other words, the amount of light used by the tree, depends upon the density of its crown, the extent of its branches, and the orientation of the windbreak. The extent of branching is of most importance in the selection of species to compose the windbreak, or, at least, in the selection of the trees which shall stand next to the field crops. The tolerance of the tree, as expressed by the density of its crown, is also to be considered.

AMOUNT OF SHADING.

Table 1 shows the total amount of light cut off by various species in both orientations and, roughly, the location of the heaviest shade as influenced by the position of the greater mass of branches. This latter point is determined by computing the percentage of the total shade that falls within a zone immediately adjacent to the trees, which has a width on either side equal to one-half of the tree height.

TABLE 1.—*Amount and distribution of shade cast by various species.*

Species and class.	Orientation east-west.		Orientation north-south.	
	Percentage of light cut off north and south sides.	Percentage of total shade within 1-ht. zone north and south sides.	Percentage of light cut off east and west sides.	Percentage of total shade within 1-ht. zone east and west sides.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
Cottonwood row, open	48.08	89.20	.....	.....
Cottonwood grove	53.10	87.55	.....	.....
Do	55.31	75.50	.....	.....
Cottonwood grove and ash	52.46	83.96	.....	.....
Cottonwood row, narrow	.....	.....	79.34	57.05
Cottonwood row, spreading	.....	.....	71.32	64.00
Soft maple belt, 3 rows	88.75	82.15	.....	.....
Green ash belt, 2 rows	.....	.....	89.77	57.29
Honey locust row	[1] 125.89	65.02	98.91	73.53
Osage orange row	[1] 113.88	71.65	[1] 116.97	65.10

[1] Where the percentage exceeds 100 it means that the amount of light cut off is greater than that which would fall upon a strip of ground as wide as the height of the trees.

Crown density and branching.—Tables 1 and 3, taken together, show that the value of the light absorbed by the trees and cut off from the crops adjacent to them is proportional to the density of the crowns. In the order of their tolerance, or ability to endure shade and thus to maintain heavy crowns, the trees may be listed as follows, with the most tolerant placed first: Osage orange, soft maple, green ash, honey locust, cottonwood. Honey locust, however, must be classed as the most severe shader of all except osage orange, and the reason is at once seen by reference to Table 2, which shows honey locust to have the most extensive branches. In this table the species are arranged in the order of their branching extent, those with shortest branches first:

TABLE 2.—*Branching extent of various trees.*

Species.	Direction.	Basis windbreaks measured.	Average height.	Average branching distance.	Relation of branching distance to height.
		Number.	*Feet.*	*Feet.*	*Per cent.*
Cottonwood	North	125	57.26	23.12	40.39
	South	98	55.02	19.92	36.22
	East	84	55.00	19.80	36.05
	West	96	59.74	20.86	34.92
	All	403	56.84	21.12	37.15
Green ash	North	28	26.33	10.58	40.25
	South	20	24.80	10.70	43.16
	East	26	27.20	11.98	44.07
	West	28	24.82	10.39	45.90
	All	102	25.84	11.18	43.30
Soft maple	North	19	35.83	16.93	47.25
	South	13	36.08	16.97	47.07
	East	3	40.67	23.33	57.38
	West	15	33.20	14.37	43.30
	All	50	35.40	16.56	46.77

TABLE 2.—*Branching extent of various trees*—Continued.

Species.	Direction.	Basis windbreaks measured.	Average height.	Average branching distance.	Relation of branching distance to height.
		Number.	*Feet.*	*Feet.*	*Per cent.*
Osage orange	North	79	17.02	9.32	54.75
	South	63	17.45	8.98	51.46
	East	85	18.36	10.01	54.50
	West	76	18.51	9.47	51.20
	All	303	17.86	9.48	53.10
Mulberry	North	22	18.23	11.00	60.36
	South	15	19.27	10.20	52.95
	East	12	21.25	12.08	56.87
	West	16	20.56	9.87	48.03
	All	65	19.60	10.74	54.80
Willow	North	48	28.11	16.58	58.97
	South	42	28.57	14.74	51.60
	East	36	26.50	16.28	61.41
	West	47	29.23	14.49	49.60
	All	173	28.20	15.50	55.00
Box elder	North	47	22.49	12.41	55.20
	South	33	22.85	12.14	53.12
	East	33	23.90	14.29	59.75
	West	36	24.03	12.72	52.97
	All	149	23.26	12.84	55.22
Honey locust	North	22	24.95	14.41	57.73
	South	21	23.35	12.91	55.30
	East	14	24.64	13.72	55.67
	West	17	26.65	15.12	56.86
	All	74	24.83	14.01	56.45

The relative shading qualities of the several species are more clearly shown by the curves on diagrams 2 to 6, inclusive. The shaded areas of the diagrams show the entire volume of light cut off from the ground. It will be seen that the high branching of cottonwood and maple permits the entrance of considerable light to the ground at the base of the trees, while the low, spreading branches of locust and osage orange create under the tree a zone in which the growth of smaller plants is quite impossible. This difference between species is especially marked in north-south windbreaks, for the morning and afternoon sun may shine under the branches unless they are very low.

Orientation.—Of greater importance than the difference between the various species in their shading effect is the difference between orientations. Table 1 shows that the amount of light used by the trees in the north-south row is considerably in excess of that taken up by the trees in a row whose orientation is east-west, and the diagrams show that this shading is not only greater in volume, but greater in extent. This is, of course, due to the fact that the north-south windbreak receives sunlight from one side or the other during about two-thirds of the day, while in the east-west row, especially in midsummer, the shadows fall little outside the area covered by the branches. Crops adjacent to a north-south windbreak will, therefore, suffer more from the shading than those adjacent to an east-west windbreak.

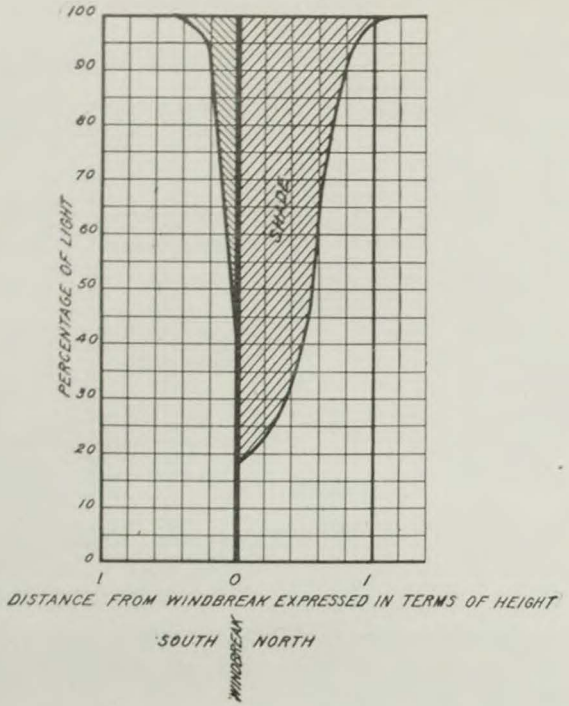

DIAGRAM 2.—Amount of sunlight cut off by cottonwood groves. Expressed in percentages of total sunlight on September 3.

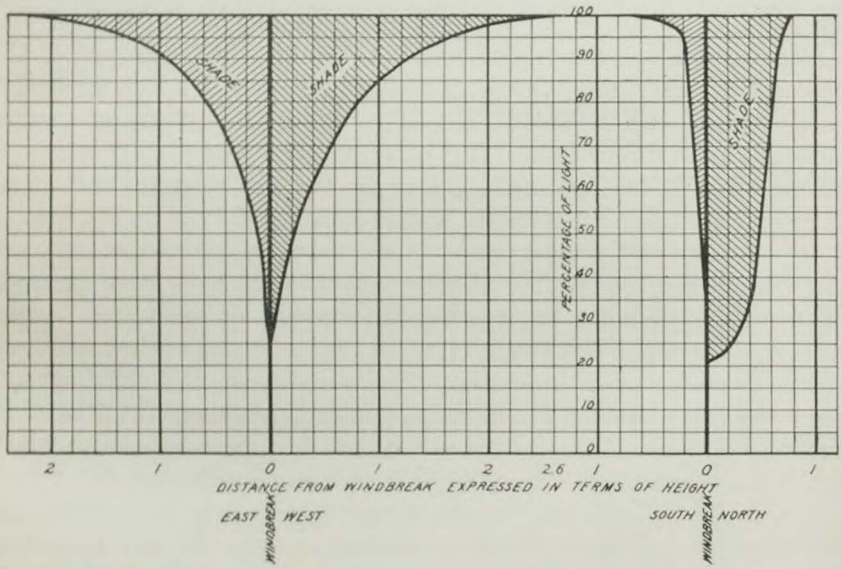

DIAGRAM 3.—Amount of sunlight cut off by cottonwood rows. Expressed in percentages of total sunlight on September 3.

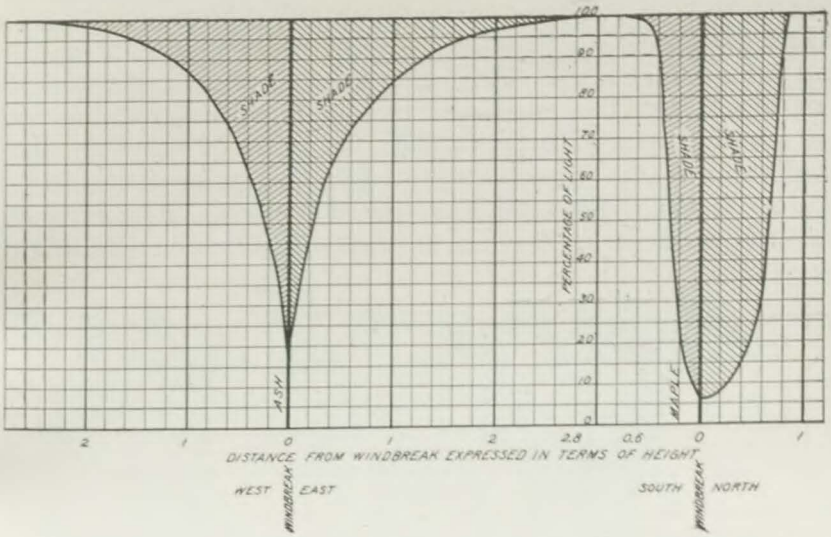

DIAGRAM 4.—Amount of sunlight cut off by ash and maple belts. Expressed in percentages of total sunlight on September 1.

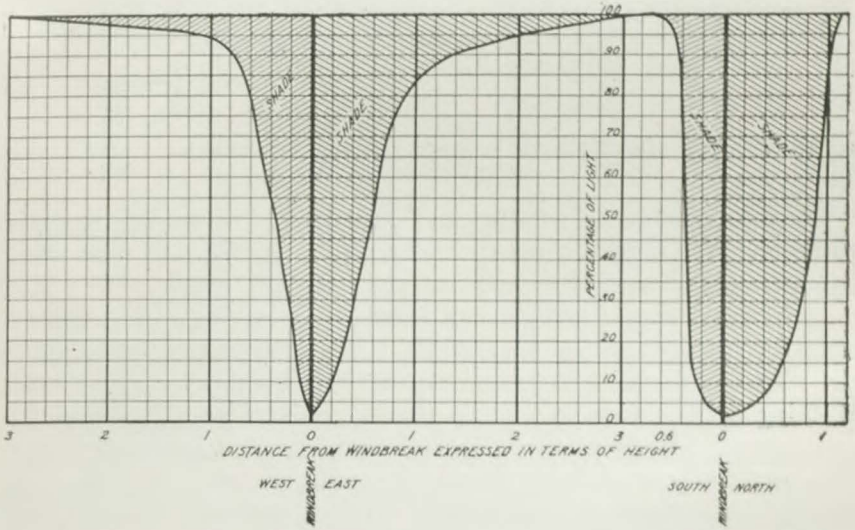

DIAGRAM 5.—Amount of sunlight cut off by osage orange hedges. Expressed in percentages of total sunlight on September 18.

A corresponding difference in the growth of the trees is also to be expected. The cottonwood windbreaks shown in Plate VI, figures 1 and 2, have thoroughly adapted themselves to this difference in the source of light. The east-west row (fig. 2) is almost devoid of lower branches and has a dense mass of foliage near the tops of the trees, while the north-south row has an even distribution of branches from the top to the bottom. The yield tables given on pp. 79–87 show the north-south rows to be proportionately larger producers of timber. In shading, honey locust again forms an exception to the general rule, since its wide branches shade an unusually large area on the north and south sides.

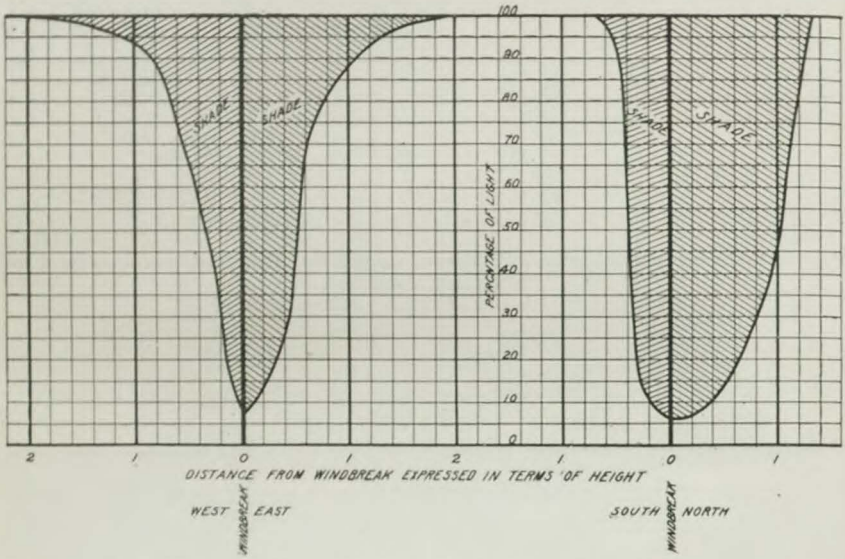

DIAGRAM 6.—Amount of sunlight cut off by honey locust rows. Expressed in percentages of total sunlight on September 19.

The ground south of windbreaks is, of course, less shaded than that to the north. It might be expected that the branches of trees would extend more toward the sun, but the southerly winds which blow during the growing season do not favor this, and the branches are to some extent bent to the north. That this is because of wind and is not a case of negative heliotropism, as some authors have suggested, is shown by cottonwood. In Kansas the greater growth of branches to the north is very marked; in Nebraska it is less marked, while in Minnesota, where southerly winds are neither prevalent nor especially drying, the deflection is much less. Willow, which is especially susceptible to this influence, shows about the same deflection in Nebraska and Minnesota, and in the latter State quite as much to the east as to the north. An exception is green ash, whose branches are not flexible.

The loss of light is found to be greater on the east than on the west sides of windbreaks, and this is in part due to wider branching on the east side. Part of the difference may also be ascribed to the greater intensity of afternoon light. The greater amount of moisture in the air in the morning has a tendency to absorb and diffuse the sunlight.

CROP EFFECTS.

Diagrams 7 to 13, inclusive, show graphically the results of the measurements of various field crops in relation to shade, and demonstrate the absolute dependence of these crops on sunlight. Table 3 expresses this in figures, which show the amount of light and the yield of various crops growing immediately adjacent to windbreaks.

TABLE 3.—*Amount of light cut off and loss to crops.*[1]

[In cornfields the moisture factor is apparently eliminated.]

Kind of windbreak.	Direction from windbreak.	Cases measured.	Light cut off.	Kind of crop.	Cases measured.	Damage to crop.
	Side.	*Number.*	*Per cent.*		*Number.*	*Per cent.*
Osage hedge	North	1	79.62	Corn	7	70.16
Do	South	1	34.26	do	3	56.73
Do	East	1	71.08	do	2	96.07
Do	do	1	71.08	Wheat	1	[2] 121.04
Do	West	1	45.89	Corn	2	77.97
Do	do	1	45.89	Wheat	4	[2] 135.31
Cottonwood row	North	1	40.74	Corn	3	63.90
Do	do	1	40.74	Alfalfa	3	64.77
Do	South	1	7.34			
Do	East	2	44.86	Corn	1	88.30
Do	do	2	44.86	Oats	5	[2] 111.85
Do	West	2	30.47	Corn	2	74.08
Do	do	2	30.47	Oats	2	95.45
Do	do	2	30.47	Alfalfa	4	74.59
Cottonwood belt	North	1	47.91	Corn	1	67.70
Do	do	1	47.91	Oats	4	79.30
Cottonwood grove	do	1	44.52	Corn	1	68.38
Do	do	1	44.52	Oats	2	67.10
Maple belt	do	1	60.46	Corn	1	61.43
Do	South	1	28.29	do	1	62.90
Maple grove	North	0		do	1	51.50
Do	do	0		Wheat	1	[2] 146.30
Ash belt	South	0		Corn	1	54.68
Do	East	1	46.28			
Do	West	1	43.49	Corn	1	[2] 103.30
Honey locust row	North	1	89.18	Alfalfa	1	84.00
Do	do	1	89.18	Timothy	1	46.60
Do	South	1	36.71			
Do	East	1	56.38			
Do	West	1	42.53	Alfalfa	1	56.25

[1] Results of studies made in cooperation with the Nebraska Agricultural Experiment Station.
[2] Where the per cent of damage exceeds 100 it means that the loss of crop was greater than the yield of a strip whose width is equal to the height of the trees.

If the damage to crops on the several sides of the cottonwood or osage orange windbreaks is compared, it is found that the loss to the crops is about proportional to and in the same area as the shadows thrown by these windbreaks. The damage is greater on the north than on the south side, and about equally extensive on the east and west sides. Although some other factor may change this relation, the shading generally does more damage to crops on the east side of the windbreaks than on the west side. In spite of this, farmers

usually think that the east side is more favorable for crop growth. That reason for this belief exists is shown in the discussion of heat, page 65.

A comparison of various crops shows that corn and alfalfa are the most tolerant of shade, and, therefore, the best producers near a windbreak. This is hardly the result to be expected, since both wheat and oats make their earlier development at a time of the year when the sunlight is less intense than that demanded by corn, and it is quite probable that the measured damage to these smaller grains represents the combined effects of shading and sapping. The importance of the latter factor is shown in the case of alfalfa (diagram 14) during a period when no rain fell and strong competition for moisture is known to have existed. It should also be remembered that wheat and oats develop at a time when the apparent position of the sun is a good way to the south, and when, therefore, the shadow on the north side of the windbreak would be much wider than at midsummer.

In many cases it was found that crops immediately beyond the shaded zone derive a benefit from the protection afforded by the trees. This resulted from the greater warmth in the area protected from wind and may, to a very slight extent, offset the damage from shading at the outer limit of the shadow. The zone of damage is appreciably less in the case of a dense grove than in that of a belt or row of trees which does not have so strong an effect upon temperature.

A remarkable case of crop growth very close to trees is illustrated in diagram 13, where the growth of corn on the west side of various tree species is compared. This shows very clearly the value of the narrow, conical crown of coniferous trees as exemplified in Austrian pine, which shades a lesser area than one which becomes larger toward the top.

REMEDIES.

The loss to crops from shading may be reduced by any of the following means:

(1) By planting, in a strip including all of the shaded zone, crops whose value is not dependent upon the production of seeds, such as blue grass, timothy (see Table 3), clover, alfalfa, Kafir corn, and fodder corn. The production of seeds in any plant requires more favorable conditions than does the growth of the vegetative parts. In Kansas an area 34 feet wide next to a row of cottonwood trees (illustrated in Pl. IX, fig. 2) gave a yield of 3 tons of Kafir corn fodder, worth $6 a ton, or about 1½ tons to the acre. Practically all of this strip would have been wasted had the owner of the land planted corn or any other grain crop upon it.

(2) By planting in windbreaks, or at least in that portion nearest the field crops, narrow and light crowned trees. Cottonwood is both

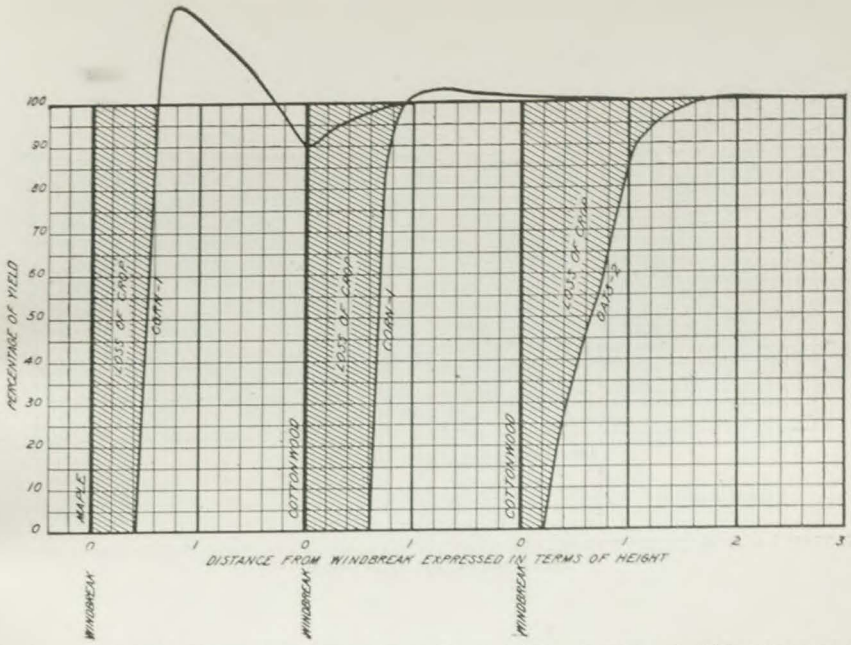

DIAGRAM 7.—Yield of crops north of dense groves. Expressed in percentages of yield at three times height.

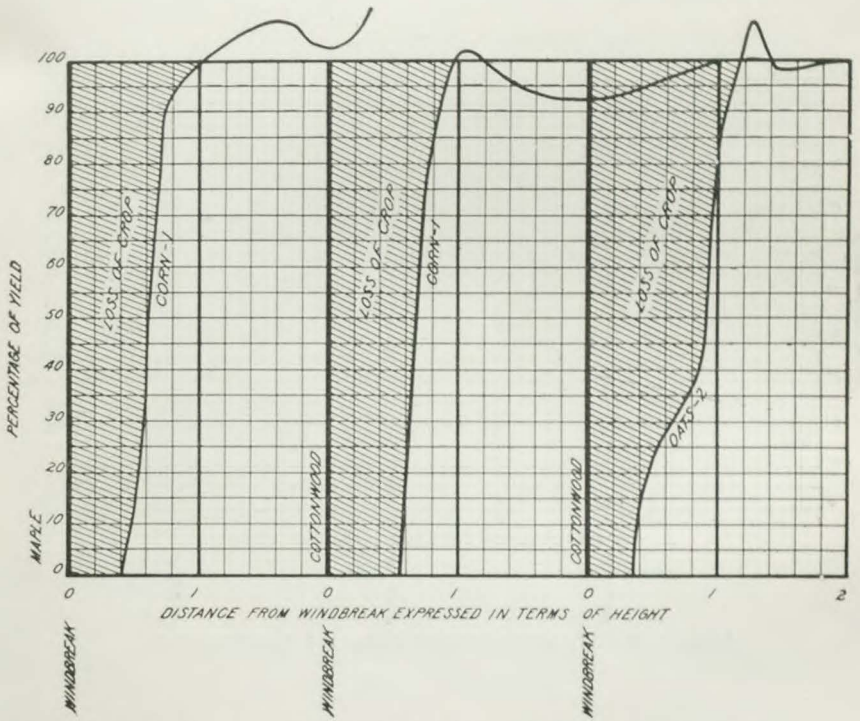

DIAGRAM 8.—Yield of crops north of shelter belts. Expressed in percentages of yield at three times height.

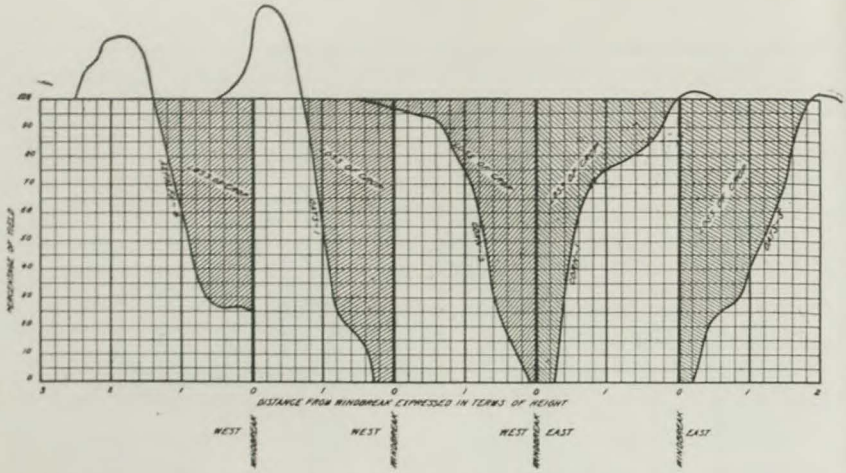

DIAGRAM 9.—Yield of crops west and east of cottonwood rows. Expressed in percentages of yield at two and one-half times height.

Normal yield in open—Osage orange.

Normal yield at two and one-half times height—Cottonwood.

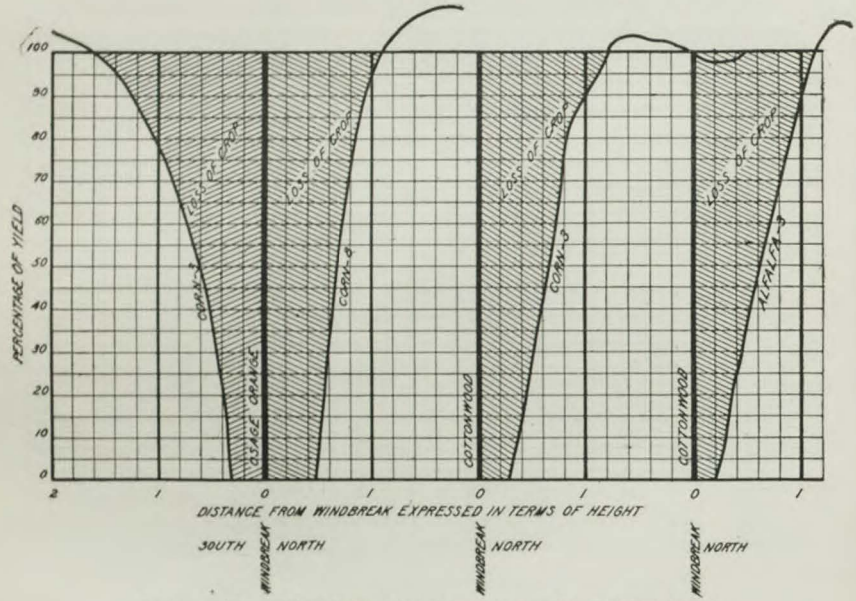

DIAGRAM 10.—Yield adjacent to osage orange and cottonwood rows.

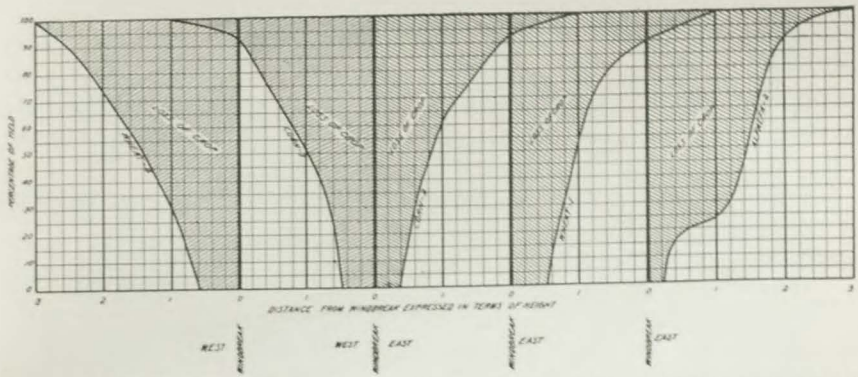

DIAGRAM 11.—Yield of crops east and west of osage orange hedges. Expressed in percentages of yield at three times height.

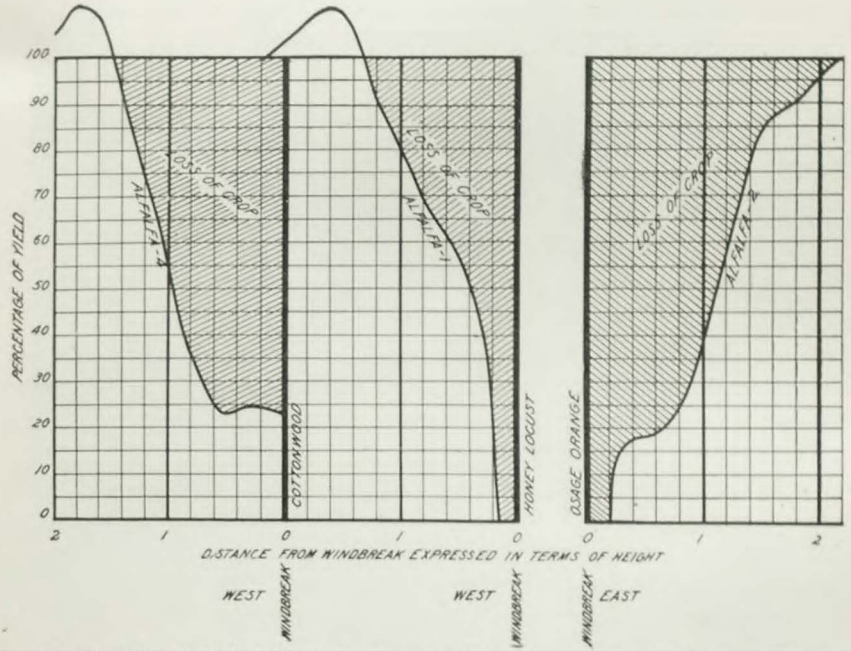

DIAGRAM 12.—Yield of alfalfa with various tree species. Expressed in percentages of yield at two and two-tenths times height.

narrow crowned and light foliaged. Maple has a narrow crown. Green ash is to be recommended. Conifers, especially Scotch and Austrian pine, white pine, and white cedar, which have narrow, conical crowns, are very desirable.

(3) The outer rows of a belt may consist of slower-growing "tolerant" trees which, unless they are of exceedingly slow growth, can be planted after the main body of trees has attained a good height. Spruce, fir, maple, and ash are good examples. Even osage orange will grow in considerable shade.

(4) The ground under the branches of tall trees may well be used for roads. Secondary roads, used only in summer, should be on the north and east sides of windbreaks.

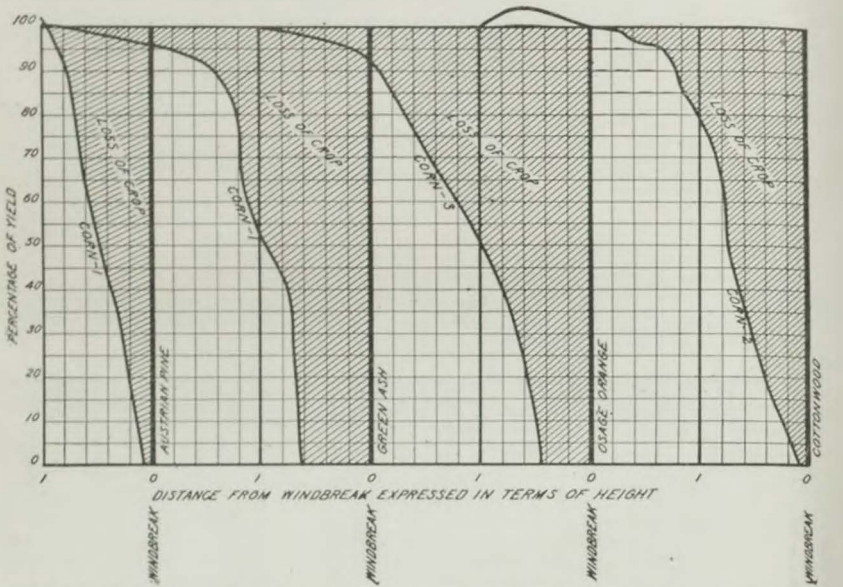

DIAGRAM 13.—Yield of corn west of various tree species. Expressed in percentages of yield at three times height.

(5) In the Middle West, where most of the winds are southerly or northerly, the east-west orientation should be established wherever possible. In the northern prairies and Lake States the north-south orientation will be found most useful.

While the damage to crops may be greater from a dense and wide-crowned species, such as osage orange, the protective value of the windbreak may be greatly enhanced by such a crown. That the protective value of a species is not necessarily proportional to its shading power, however, is brought out later under the subject of evaporation (p. 45) in the discussion of windbreak efficiency.

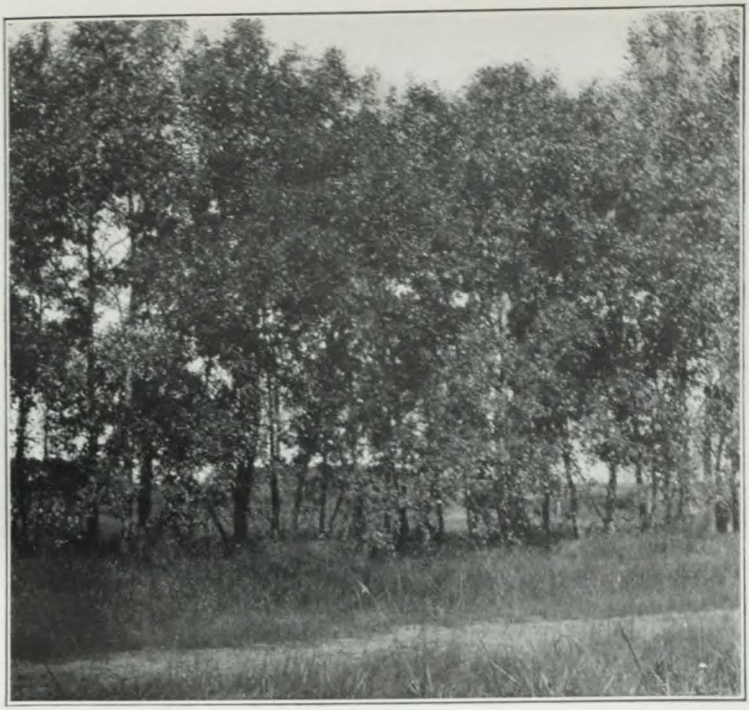

FIG. 1.—THE BRANCHES OF ASH ARE SMALL AND SHORT, AND THE TREE DOES LITTLE DAMAGE BY SHADING CROPS.

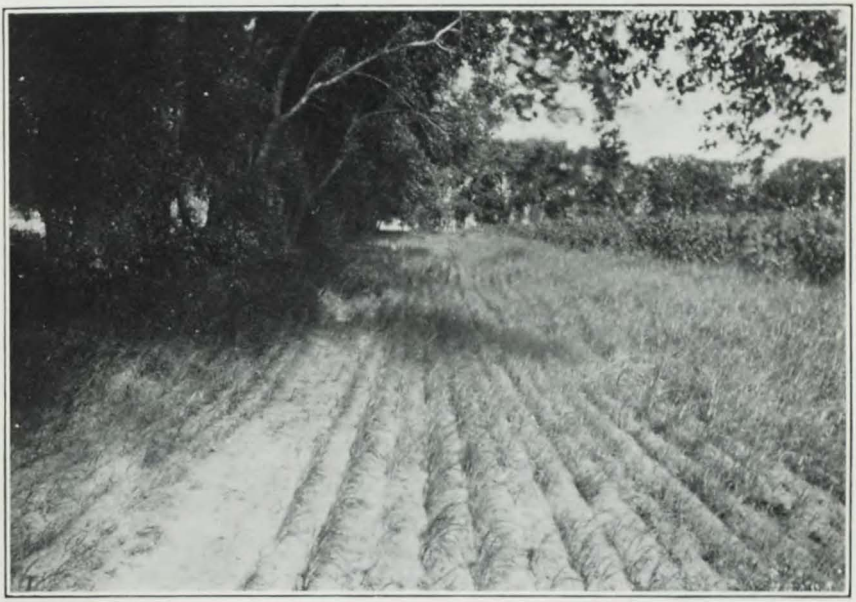

FIG. 2.—KAFIR CORN WILL PRODUCE FORAGE WHERE CORN WOULD PRODUCE NO EARS.

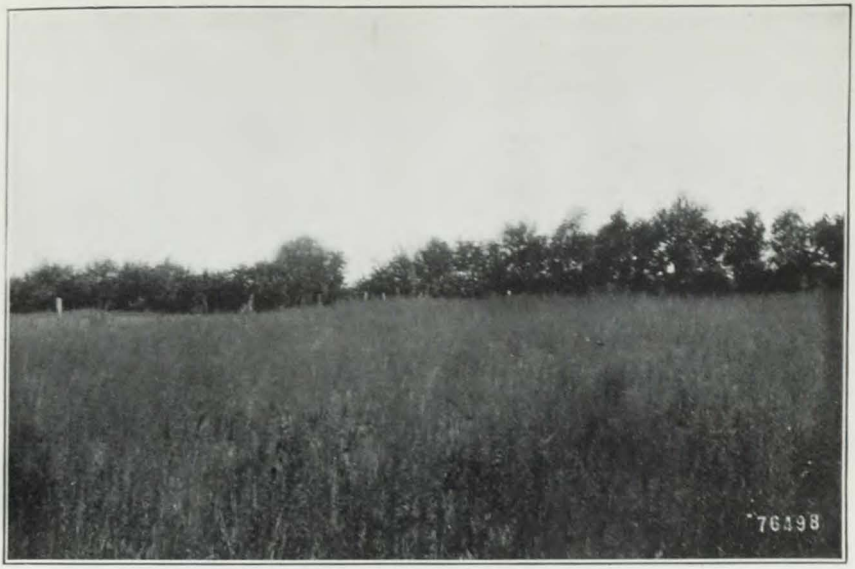

FIG. 1.—EFFECT OF CULTIVATION ON OSAGE ORANGE.

Left side, no cultivation; height, 13 feet; root extent, 35 feet; value in posts, $121 per mile. Right side, cultivated one side; height, 16 feet; root extent, 17 feet; value in posts, $296 per mile.

FIG. 2.—LARGE TREES NOT ONLY TAKE THE MOISTURE AWAY FROM THE NEAREST TREES IN THE ORCHARD, BUT ALSO INJURE THEM BY SHADING.

II. SOIL MOISTURE—SAPPING.

It is very commonly stated that the damage done by windbreaks is due to the "sapping" of the soil by the roots of the trees, which are said to take not only large quantities of the moisture needed by crops, but also the soil fertility. The matter of soil fertility is considered separately in this bulletin. That the importance of sapping is usually overestimated was very apparent in the season of 1908, when moisture was abundant even in the root zones of windbreaks,

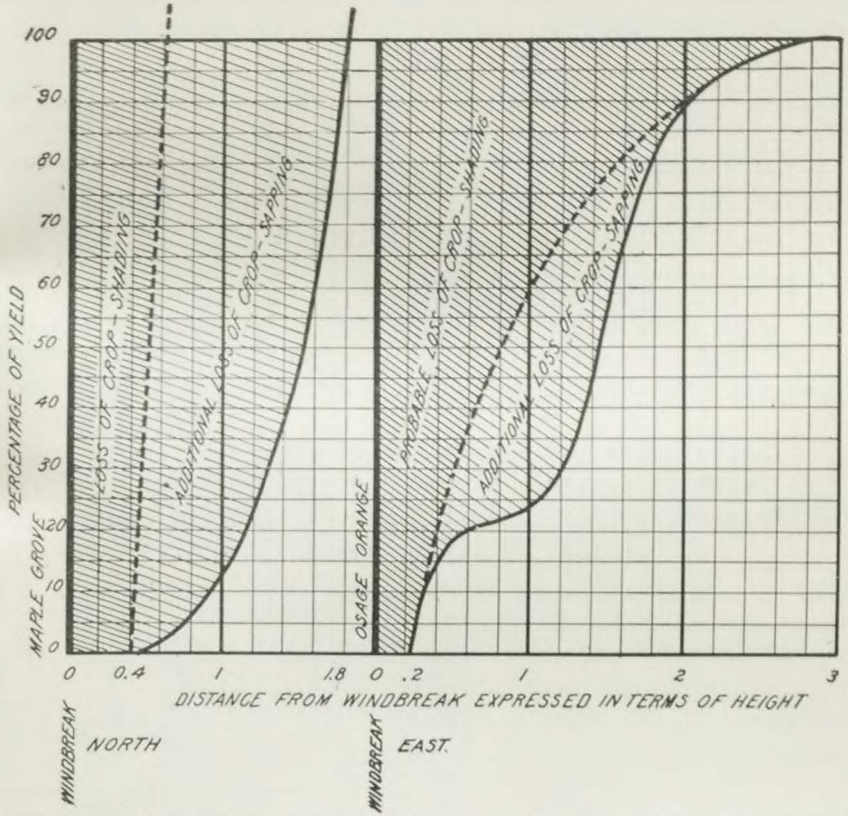

DIAGRAM 14.—Effects of shading and sapping on the growth of field crops. Relative importance of two factors on north and east sides.

but when the effects of shading were perfectly clear. The effects of these two factors are easily confused and difficult to separate.

EXTENT OF SAPPING.

No attempt has been made to determine what *quantity* of soil moisture is taken by trees in a windbreak, since it may be supposed that in exceedingly dry years this may be sufficient to practically prohibit the growth of field crops in the zone permeated by the well-established roots of the trees. Such being the case, it is of greatest

interest to determine the *extent* of these roots and the area which may be so seriously affected in the driest years by different species.

The soil surveys previously described indicate the limits of the tree roots, in some instances by the depression of the moisture curve at the tips of the roots and in all cases by the sudden increase in moisture when the ends of the roots are passed. The point farthest from the trees, where there was appreciable depletion of the moisture, has been accepted as the limit of the tree roots. Table 4 indicates the root extent of all species studied in distances at right angles to the windbreaks concerned.

TABLE 4.—*Average root extent of various species in windbreaks.*

Species.	Direction.	Cases measured.	Average height.	Average sapping.	
				Distance.	Proportion to height.
		Number.	*Feet.*	*Feet.*	*Per cent.*
Osage orange	North	28	19.11	31.21	163.3
	South	20	20.70	25.25	122.0
	East	8	18.38	33.37	181.5
	West	12	19.50	37.25	191.0
	All	68	19.56	30.78	157.3
Green ash	North	3	22.67	33.33	146.9
	South	5	45.00	42.80	95.1
	East	2	50.00	60.00	120.0
	West				
	All	10	39.30	43.40	110.4
Cottonwood	North	23	58.16	73.61	126.3
	South	17	60.94	61.59	101.0
	East	10	59.00	61.50	104.2
	West	10	55.00	49.00	89.1
	All	60	58.60	64.08	109.3
Mulberry	North	2	12.00	20.00	166.7
	South	1	14.00	32.00	228.5
	East	5	22.80	49.00	215.0
	West	1	14.00	45.00	321.4
	All	9	18.44	40.22	218.0
Honey locust	North	3	35.00	38.00	108.6
White pine	North	1	20.00	9.00	45.0
	South	1	20.00	15.00	75.0
	All	2	20.00	12.00	60.0
Scotch pine	West	3	24.00	40.00	166.7
Austrian pine	do	3	30.00	50.00	166.7

From the data given it is evident that, contrary to the common opinion, cottonwood has the least extensive roots of any of the broad-leaf species, and hence has the least power for damage to crops in dry years. Next in order come green ash, osage orange, and mulberry. The data given for honey locust are too meager to form the basis of any good estimate of its sapping powers. Of the conifers, white pine shows a distinctly compact root system, while Scotch and Austrian pines are, in the situations studied and habitually, much longer rooted. The figures given for the last two species are

doubtless magnified by the effects of competition, since the roots were necessarily one-sided. The importance of this is shown later.

CONDITIONS THAT INFLUENCE ROOT EXTENT.

While each tree species has a distinct root form—tap or lateral—each shows more or less adaptability to the moisture conditions under which growth is made. Lack of moisture induces long roots. Hence, to compare cottonwood, which is invariably planted on moist situations, with osage orange, which is commonly found on the drier ones, is not quite fair to the latter. A careful study of the original data on which Table 4 is based indicates that there are a number of conditions which reduce the amount of moisture available for the trees and hence stimulate root growth into the good soil of fields, where it is undesirable. The causes of extensive roots are as follows:

(1) Lack of rainfall. Where the rainfall is light the roots will go far in search of moisture.

(2) Light and infertile soils.

(3) An impermeable subsoil. Stiff clays and gumbo can not be penetrated by the roots, nor do they permit moisture from lower strata to reach the roots.

(4) Lack of capillary water. This is greatest when the water table is very low.

(5) A heavy soil cover of grass or other deep-rooted plants. Cultivation in the root zone conserves the moisture and hence reduces the necessity for long roots. The effect of cultivation on the root extent of osage orange is clearly shown by Table 5.

TABLE 5.—*Effect of cultivation on root extent of osage orange.*

Amount of cultivation.	Cases measured.	Average height of trees.	Average root extent.	
			Distance.	Proportion to height.
	Number.	*Feet.*	*Feet.*	*Per cent.*
None	8	20.0	43.7	218.7
One side of trees	25	17.2	28.9	167.8
Both sides of trees	35	21.7	29.2	134.5

It must be seen from these figures that where the ground adjacent to windbreaks is not cultivated at all the roots will gain possession of a much larger area than where one or both sides are cultivated.

(6) The presence of other trees competing with those on the edge of the windbreak for the soil moisture. Trees on the edge of a grove will have practically a one-sided root system, and this, of course, must be more extensive, in the direction in which moisture is easily found, than the roots of trees in a single row, which extend freely in both directions.

TABLE 6.—*Effect of competition on root extent of cottonwood.*

Kind of windbreak.	Cases measured.	Average height of trees.	Average root extent.	
			Length.	Proportion to height.
	Number.	*Feet.*	*Feet.*	*Per cent.*
Single row	16	57.0	53.6	94.1
Two or three rows	27	52.1	56.3	108.1
Groves	17	70.5	86.3	122.5

(7) Coppicing or cutting back of hedges. Coppicing does not directly increase the length of roots, but leaves the new shoots to grow with roots of the same length as those possessed by the original trees. In the case of osage orange this is seen to have a very important effect.

TABLE 7.—*Effect of coppicing on proportionate root extent.*

Kind of windbreak.	Cases measured.	Average height of trees.	Average root extent.	
			Length.	Proportion to height.
	Number.	*Feet.*	*Feet.*	*Per cent.*
Seedling growth	31	15.6	30.2	193.5
Coppice growth	6	13.0	33.0	254.0

The conditions stated above will, singly or collectively, account for the unusual length of roots in almost every instance where they are found to be longer in proportion to the height than is given in Table 4. These conditions should be avoided as far as possible.

EFFECTS OF SAPPING.

As already stated, the effect of a lack of moisture in the zone next to the trees will be felt most strongly by plants which begin life anew each year; that is, by annual crops. Frequently seeds will fail to germinate, or the young plants will die from lack of moisture before their roots can be developed. It is believed that the ability of perennial crops, like alfalfa and clover, to grow in the shade of trees is in a large measure due to their extensive roots.

Orchards.—Fruit trees on the edge of the orchard where they must compete with forest trees are usually small in size. Doubtless this is partly due to shading. Even if the trees attain to good bearing the fruit in dry years is likely to be small and of poor color. In California trenches are dug to cut off the roots of eucalypts and other large trees surrounding orchards in order to prevent their taking moisture from the fruit trees.

A case measured in Edwards County, Kans., shows that while sapping by forest trees may be appreciable, it need not, in a young orchard, result in any damage to the fruit trees. The windbreak consisted of two rows of cottonwood 15 feet high and 10 feet apart. Ten feet to the north was a row of 22 peach trees and 15 feet farther was a second row containing the same number of trees. The results of tree and soil measurements are shown in Table 8.

TABLE 8.—*Relation of orchard and forest trees.*

	Average soil moisture at depth 40 inches.	Average height of trees.
	Per cent.	*Feet.*
Cottonwood rows	14.65	15.00
First row peach trees	9.62	7.36
Second row peach trees	11.75	6.36

Although moisture was not abundant and the cottonwoods had to some extent robbed the first row of fruit trees, the shading effect was not felt and no damage had so far resulted. Instead, the trees nearest the windbreak seemed to be doing better than those in the second row.

Grainfields.—In grainfields the effect of sapping is shown by the smaller size of the plants and smaller heads of grain. Even if there is abundant moisture when the plants are young, and they attain good size, a late drought will parch them badly. The fields first become "burned" or "fired" along the edges where there are trees or heavy sod. With small grains the result is usually the premature ripening of the heads and loss of the grain by shelling out. With corn, the ears are reduced in size and the kernels do not fill out. In an instance examined in the fall of 1908, immediately after the first frost, it was shown that the effect of the tree roots (green ash) had been to cause the earlier ripening of the corn, especially that growing near the tips of the roots. The advanced ripening was evident not only in the kernels of corn but also in the plant.

With one or two exceptions, the effect of sapping was not apparent in corn yields, which increased very steadily once the limit of the shaded zone had been reached. In the exceptional cases there is a sudden checking of the rise of the yield curve, indicating the zone of activity of the tree roots. With oats and wheat, however, the influence of tree roots was much more apparent in all cases (see diagrams 7 to 13). Both of these small grains suffered from lack of moisture early in the spring before corn had been planted. In a field of wheat north of a grove of soft maple (see diagram 14) the grain was notably poor for about 45 feet from the trees, which were 29 feet high.

Beyond this there was a sudden increase in the size and number of the plants, which were, for a short distance out, larger than the normal for the field. The total loss was 146.3 per cent of the possible yield on a strip as wide as the height of the tree. If there is deducted from this the 51.5 per cent lost in cornfields, where there is damage only from shading, the 95 per cent left represents the sapping damage of soft maple roots extending to the north.

A similar effect was found in the case of alfalfa east of an osage orange hedge (see diagram 14). No rain fell during the month in which this (the second) crop matured, and at its end the dearth of moisture in the root zone was quite marked. In this case the sapping damage was 20 per cent in addition to the normal effects of shading on the east side of osage hedges.

The season was too moist to furnish examples of the most severe damage from sapping. It is safe to say, however, that in cases of extreme drought, the loss of annual crops may be complete to the outer limits of the tree roots.

REMEDIES.

Damaging competition for moisture between forest trees and smaller forms of vegetation may be greatly lessened in any of the following ways:

(1) By thorough cultivation of the soil adjacent to the trees, increasing the moisture of the lower soil, and decreasing the necessity for wide root extension on the part of the trees. With rows and hedges along roads a strip between the trees and the road should be cultivated in order to induce root growth on that side.

(2) By very deep plowing each year alongside of shallow-rooted species, such as osage orange and mulberry, in order to cut off the surface roots.

(3) By deep plowing or even dynamiting of the subsoil in extreme cases, before planting the trees, to encourage deep rooting, and to facilitate the upward capillary movement of moisture.

(4) By the use of seed crops, such as timothy and other grasses, clover, and alfalfa, next to the trees. This should not be done until the trees have attained the height desired for protective purposes, since the competition of these crops will in a large measure check the growth of the trees.

(5) By planting tap-rooted species like white pine, Norway pine, oaks, hickories, and maples on the edge of the grove or belt adjacent to crops.

III. SOIL FERTILITY.

Farmers often lay much stress upon the fact that the trees in a windbreak seem to sap the fertility of the soil along their borders. Careful studies of the requirements of various forest trees have shown

that there is little basis for such an opinion, for, while all trees, and especially some of the hardwoods, require a certain amount of soluble salts, almost all of this material is returned to the soil when the leaves fall.

The matter of soil fertility has received very little attention in this study. A few samples of the surface soil (depth 1 foot) were taken, however, to determine the effect of the tree roots upon the quantity of the essential salts at various distances from windbreaks.

No single element is more essential to all forms of plant growth than nitrogen, though phosphorus and potassium are very essential to the formation of seeds. Nitrogen is an important component of saltpeter, of manure, and of many commercial fertilizers. Nitrogen is present in the soil in many chemical combinations, but is available to plants only in the form of nitrates. The quantity of nitrates available in any soil depends not only upon the total amount of nitrogen which may be present, but also upon the physical properties of the soil, its moisture, warmth, and porosity, all of which limit the activity of the microorganisms.

ANALYSES FOR NITROGEN.

Soils were analyzed for their total nitrogen and their available nitrates in three fields adjacent to cottonwood windbreaks and in three adjacent to honey locust. Cottonwood is usually considered the most severe drainer of the fertility of the soil. Honey locust, being a legume, should have a decidedly different effect upon the supply of nitrates. The results of analyses for both trees show a smaller amount of available nitrates in the zone permeated by their roots, but do not show any decrease in the total amount of nitrogen in the soil. In other words, there has been no drain upon the store of those substances which go to make up the nitrates for plant food.

On the north side of a belt of cottonwood trees, the smallest proportion of nitrates and the lowest amount of water are found in the same position relative to the windbreak. The conclusion is that the smaller quantity of nitrates is not an indication of their use by the trees, but is due to a deficiency of the moisture on which the activity of nitrifying bacteria is dependent. Exactly the same relation holds in the case of honey locust. In each instance the amount of nitrates is least at the point where the activity of the roots has most markedly reduced the amount of moisture. It can not be said, then, that forest trees reduce the fertility of the soil in nitrogen, although their use of soil moisture may reduce the activity of the nitrifying bacteria and cause *temporary sterility* in the zone of root influence.

IV. MECHANICAL POWER OF WINDS.

A Russian experimenter[1] has shown that the air which strikes a body of trees is to some extent deflected upward; some of it leaks through between the leaves and branches and some of it may pass under the trees. The amount deflected upward is greatest in the case of trees which are not too rigid. Willows are typical of the class of trees which have this effect. These are very unimportant considerations.

In general, there is a mass of more or less calm air in the lee of the windbreak which in time is set in motion by contact with the rapid-moving strata above. Where a strong current of air passes under the trees (see diagram 33) it gradually loses its velocity through friction with the ground and with a calmer stratum of air above, so

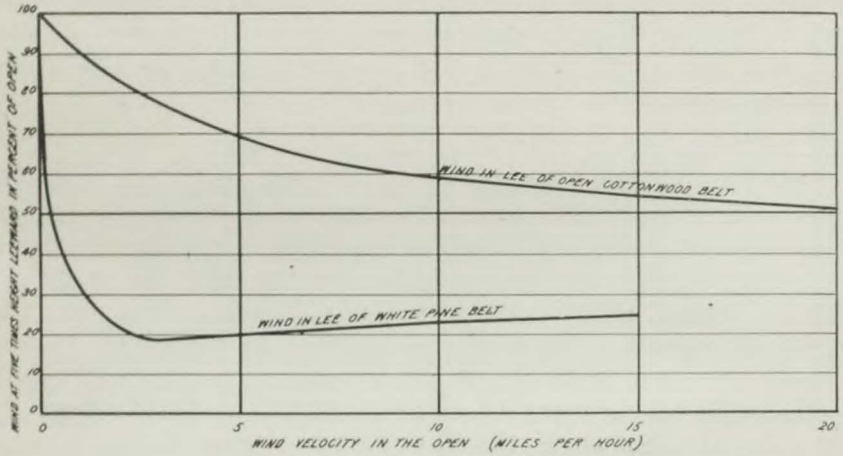

DIAGRAM 15.—Reduction of mechanical force of wind.

tnat the wind velocity at the ground may be greater near the trees than somewhat farther away on the leeward side.

Distances at which the calming effect of the windbreak may be felt will depend upon the depth of the mass of the air so calmed (which will, of course, be equal to the height of the trees), and also upon the mean velocity of the air in the area of calm (determined by the leakage through the windbreak). Actually the average distance was found to be not more than twenty times the height of the windbreak, and at that distance almost the same velocities were experienced as were found on the windward side of the windbreak.

When planting windbreaks for the protection of buildings or fields from violent winds the farmer is most concerned with the effect upon wind velocity in the immediate vicinity of the trees. A com-

[1] Nesterov, N. S., "The Influence of the Forest on the Force and Direction of the Wind." Lumber Trade Journal, Moscow, 1908, Vol. X, Nos. 8 and 9.

FIG. 1.—LUXURIANT GROWTH OF ORCHARD TREES IN CENTRAL KANSAS; INCLOSED BY COTTONWOOD GROVE AND PROTECTED FROM MECHANICAL AND DRYING POWER OF WIND.

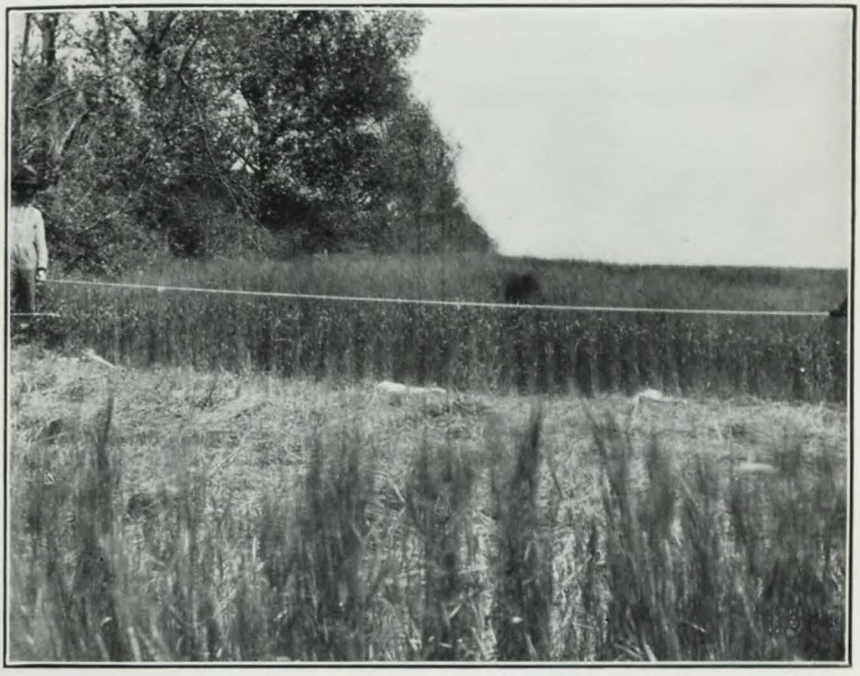

FIG. 2.—WHEAT NEAR THE TREES HAS BEEN BENEFITED BY THE COVERING AFFORDED WHERE SNOW DRIFTED IN THE LEE OF THE WINDBREAK.

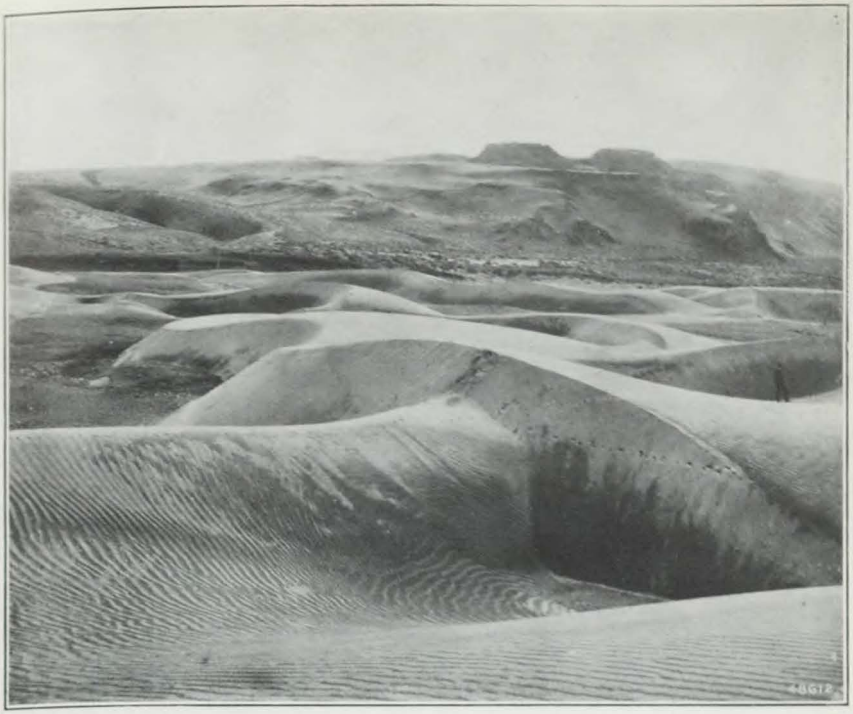

FIG. 1.—DUNES OF SAND BLOWN OUT OF THE BED OF THE COLUMBIA RIVER, SHERMAN COUNTY, OREG.

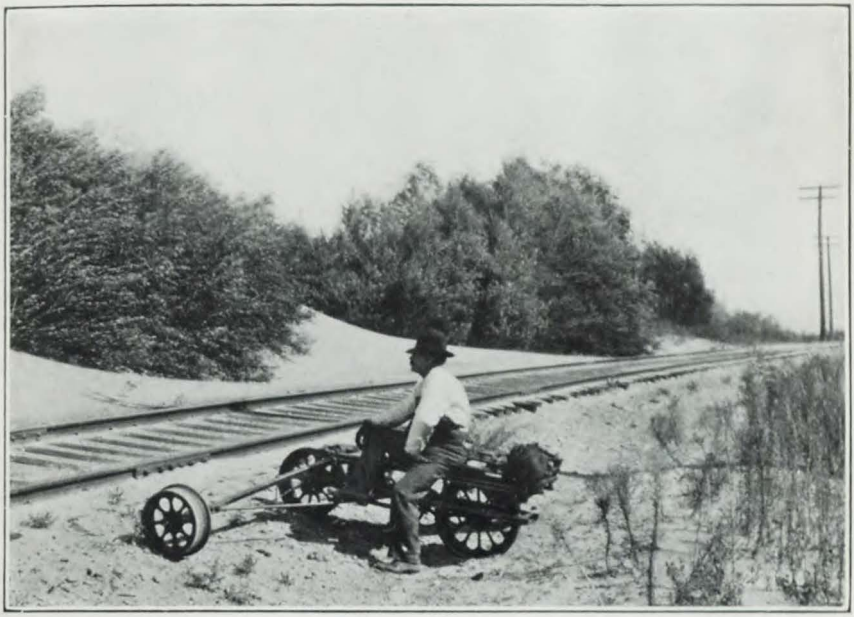

FIG. 2.—SAND ENCROACHING ON A RAILROAD TRACK, HELD IN CHECK BY PLANTING OF WILLOWS. NEAR THE DALLES, OREG.

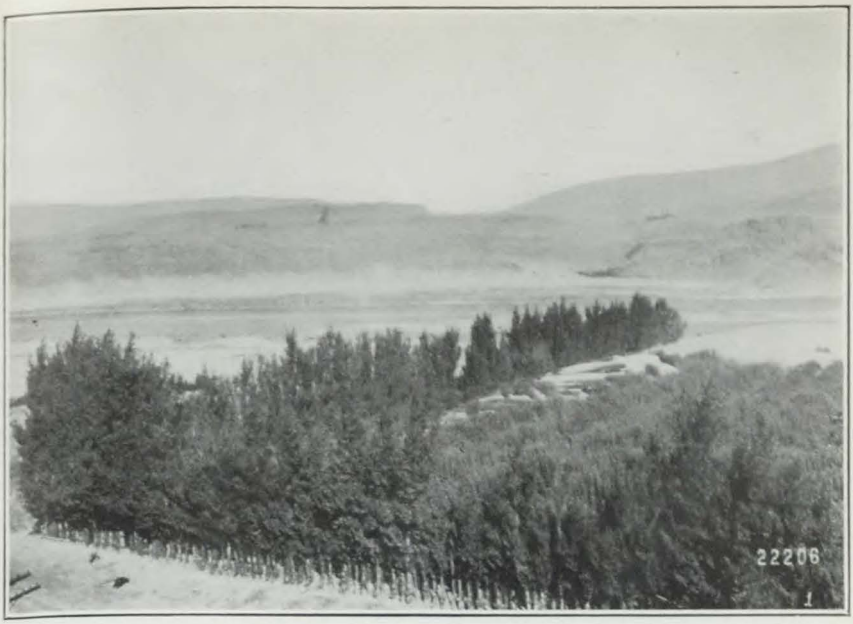

FIG. 1.—LOMBARDY POPLAR PROTECTING AN ORCHARD.

FIG. 2.—IN THE ARKANSAS RIVER VALLEY DENSE HEDGES OF MULBERRY AND OTHER WINDBREAKS PROTECT ORCHARDS FROM WIND AND FROM DRIFTING SAND.

parison of the wind movement at a point in the open with that at a point 5-ht. in the lee of the windbreak shows that a wind which reaches a velocity of 25 miles per hour in the open will in the shelter of a good windbreak have a velocity of only 20 per cent of this, or 5 miles per hour (see diagram 15).

DAMAGE TO CROPS.

In August, 1908, an opportunity was afforded for observing the effect of a violent wind upon a field of corn in the shelter of a windbreak which consisted of three rows of willows, 80 rods long, with a mean height of about 28 feet. With a wind velocity of at least 50 miles per hour about half of the corn in unprotected portions of the field was blown to the ground, while the remainder was bent about halfway to the earth. Since the ears were "in the milk" at the time, the field, in its damaged condition, could not mature more than one-third of a normal crop.

In the shelter of the windbreak there was no damage. This held true to a distance of about 6-ht., or 10 rods. Between 6-ht. and 8-ht. there was very slight damage to the corn, perhaps 10 per cent loss. From 8-ht. to 12-ht. there was a loss of perhaps one-fourth of the crop, while beyond the latter point, the benefit from the windbreak was not appreciable. Assuming a normal yield of 45 bushels per acre, the protective value of the windbreak in this storm may be valued at 260 bushels. In addition, the windbreak has more than paid for the ground occupied through its present value in posts and fuel. The posts alone are estimated at $317.

Mr. O. B. Galusha,[1] of Illinois, writing in 1869, describes a storm in 1862 which struck the northern part of Illinois and did so much damage to standing corn that the monetary loss would be almost sufficient to pay the expenses of planting 4 miles of shelter belt on every section of land in the region affected.

MOVEMENT OF SOILS.

The effect of winds in moving loose soils has often proved disastrous to farmers. There have been many instances of great damage from this source, but in years when winds are not prevalent and when moisture is abundant, they are likely to be forgotten.

Prof. F. H. King [2] described in detail the effects of a strong northeast wind in the northern part of Wisconsin in moving the soil of cultivated fields. The wind occurred immediately after a heavy rain, and in a very short time the surface soil was dried out, the smaller particles being carried off the fields and deposited wherever the velocity of the wind was checked. The value of fences, hedges,

[1] Report on Forestry, 1877; F. B. Hough.
[2] Bulletin 42, Wisconsin Agricultural Experiment Station.

groves of trees, and other factors which prevent this movement of the soil, is described in detail, and a systematic planting of windbreaks for the protection of fields is very strongly urged.

The sand hills of Nebraska furnish another striking example. In years of plentiful moisture many fields in that section can be cultivated profitably, yet at any time winds may begin to move the soil and the "blow-out" may continue until the water table is reached. Unfortunately, the farmers in this region have never fully appreciated the value of windbreaks, and are again cultivating areas which, in dry years, will prove to be valueless without protection from winds.

Damage of this sort does not stop with the taking up of the soil from one field, but may be quite as great in another field where the soil is deposited.

The sand hills south of the Arkansas River in Kansas have been built up, it is said, from sand blown out of the bed of that river at times of low water. Similar conditions exist in the Columbia River Valley in Washington and Oregon, where the sands from the river are picked up and carried on to adjoining fields, with the result that crops are completely buried and much damage is done to fruit (Pl. XII). In a case of this sort the larger particles of sand are rolled along the ground rather than lifted into the air. In the Columbia River Valley a simple strip of grain planted near the bank of the river has sometimes been found to be very efficient in catching the sand. Of trees planted in this region the Lombardy poplar has been found best adapted to the situation, and very soon forms a protective barrier about orchards and grain fields. Railroads are compelled to construct numberless "hurdles" or low board fences to check the moving sand which threatens to bury their tracks. Willows have in some cases been planted successfully and serve the purpose as well as fences (Pl. XII, fig. 2).

In the Arkansas River Valley, where there are extensive orchards, it was early discovered that they must have the protection afforded by hedges and belts of trees. Russian mulberry has proved very valuable for this purpose, at the same time baiting the fruit-eating birds, which would otherwise destroy the more valuable crop.

It is commonly supposed that heavier soils are not likely to be moved by winds to an extent to damage crops. In Marion County, Kans., however, the movement of the soil, a moderately heavy fine loess, 25 or 30 years ago threatened the usefulness of the farm lands of that section. Soil drifts several feet deep can still be seen in lanes and along roads, which were at that time protected by low hedges or fences, which formed traps. With the planting of many hedges of osage orange the movement of soils ceased.

DRIFTING OF SNOW.

A shelter belt may be so placed as to act as a "snow trap," since the snow will be dropped in the lee of the windbreak, where the force of the wind is slight. On this account objection is often made to windbreaks which stand on the north or west side of roads and which cause a large amount of snow to be deposited in the road. This may to some extent be prevented by placing the windbreaks on the side of the road opposite to that from which the prevailing winds come, or, better still, by making the windbreak on the windward side of the road wide enough to completely check the wind and to collect the greater mass of snow under the trees.

Railroads are particularly interested in windbreaks for snow protection, since even a light fall of snow, if blown into a railroad cut, may stop traffic. To protect their tracks from snow, railroads have, in mountainous regions, constructed many miles of snow sheds, and in the Plains region have placed artificial windbreaks in the form of board fences, often in series, at some distance from the track, on the windward side. A few desultory attempts have also been made to protect railroad cuts with bodies of timber, but in most cases the wrong species were selected, little care was given the trees, and the windbreaks are a practical failure. Yet this scheme of protection, if properly carried out, would not only save the railroad companies large outlays for the construction and maintenance of their fences, but would utilize the land within their rights of way for the production of posts and ties, and prove of esthetic value as well. The practical objection to this would be the necessity for acquiring wider rights of way on the windward sides of the cuts.

V. EVAPORATION.

Except when it is completely saturated, the air[1] is constantly taking up moisture from the surface of ponds, from the soil, from the foliage of vegetation, and even from bodies of snow and ice, and this evaporation is always enhanced by any movement which has the effect of distributing the aqueous vapor as it is formed, and thereby preventing local saturation. The change to the vaporous state requires a great deal of heat. This heat is in part supplied by the air and partly by the object which is losing its moisture.

[1] The term "air" is used in the popular sense throughout this and other discussions. It is well understood that the formation of aqueous vapor is independent of the air, and that this gas is only mixed with the gases of the air—not a part of it. The temperature and dissemination of aqueous vapor are so entirely dependent upon the temperature and movement of the air, however, that the two terms become inseparable in common usage.

IMPORTANCE OF EVAPORATION.

Evaporation of moisture from the soil is considerable in amount, but depends more upon capillary action, which brings moisture to the surface, and upon the direct heat of the sun, than upon the rate of wind movement. The chief part played by the wind is to carry off the moisture as rapidly as it is evaporated from the surface. Only when the surface is wet from a recent rain is the action of wind apparent in drying out the uppermost crust of the soil, but this influence is so slight that it is not appreciable in soil samples taken at a depth of 4 inches. The upward capillary movement of soil moisture may be reduced by from 80 to 90 per cent by a covering of loose soil or other mulch. In checking evaporation from the soil, therefore, protection from wind will be an unimportant item, except in the effect upon the evaporation of rain water, or irrigation water, before it has opportunity to soak into the ground.

Evaporation or "transpiration" of moisture from the leaves of plants, whether grasses, field crops, or trees, is much greater than the direct evaporation from the soil, which, when the soil is covered with vegetation, as in fields, becomes comparatively unimportant.

Transpiration or loss of moisture from the leaves of plants is a natural function and is going on constantly, but is only in a moderate degree necessary to the vigorous growth of the plant. It is always a source of great loss of moisture, is greatly increased by unfavorable atmospheric conditions, and may easily become so excessive as to be very injurious to the plant. Normally there is an unavoidable loss of moisture through the pores or "stomata" and a slight loss through the epidermis of the leaves. Usually when evaporation exceeds the supply of moisture to the leaf the stomata are closed.

Many cases have been observed in which the evaporative or desiccating power of the wind has had a most marked effect upon the growth, or even the very existence of vegetation. The most extreme cases were in the Middle West a few years ago, when, after long periods during which the rainfall had been hardly sufficient for crop growth, hot, dry winds blew across the prairies of Kansas and Nebraska, bringing almost complete destruction to the field crops of the region. Often in a day or two crops which had given fair promise of success were parched to crispness. The same effect is produced upon the half-dormant plants in a field of winter wheat, when, their protective covering of snow removed, they are subjected to a desiccating wind. In all such cases a windbreak is very beneficial to vegetation, not only because it checks the mechanical force of the wind, but because the stagnation of the air permits the formation of a more or less complete blanket of humid air or, in other words, the rapid dissemination of the moisture is stopped.

The loss of moisture by evaporation is the crucial feature of the effect of winds upon crops. A fair estimate could be made of the effect of the windbreak in modifying those atmospheric factors which cause transpiration, by the use of evaporometers, exposed to the same conditions as were the plants in the fields.[1]

The distance to which a windbreak may protect objects on its leeward side has been variously estimated at from ten to fifty times its height. While some experiments have been carried on to determine this point (see diagram 18), it has in general been assumed that the influence, if any, was not of great importance beyond ten times the height of the trees.

WINDBREAK EFFICIENCY DETERMINED BY EVAPORATION.

The object of the evaporometer readings was to determine the effect of a windbreak upon the amount of evaporation in the area which it protects. If this evaporation is expressed as a percentage of the evaporation in the open during the same period, the figure may be used as a measure of the degree of efficiency of the windbreak at the particular point where the instrument was exposed, and the simultaneous measurements of evaporation at several points in the affected zone will form a basis for a curve which may be called "the efficiency curve" for the windbreak, under the given conditions of wind.

Tests have been made on a large number of windbreaks of various kinds and of different degrees of density or thickness, to determine the comparative efficiency of windbreaks of the several classes and to discover, if possible, how large a mass of trees is needed to form a barrier against the most powerful winds.

The results obtained for windbreaks of the same class have been averaged to show the efficiency of the windbreak with all wind velocities which occurred during the period of observation. In order to simplify the demonstration only the efficiency figures with wind velocities of 5 miles per hour or a multiple thereof have been used. These are given as "efficiency curves" for the various classes of windbreaks, on diagrams 16 to 24, inclusive.

The conclusions to be derived from the curves representing the protection afforded by a single windbreak against winds of various velocities, and from comparison of the curves which show the efficiency of different kinds of windbreaks, are as follows:

(1) The efficiency of a windbreak in checking evaporation is proportional to its density. It may save at a single point in extreme cases 70 per cent of the moisture ordinarily lost by evaporation.

[1] No claim is made for the accuracy of the comparison between the quantity of water evaporated from this instrument and that transpired from a leaf under similar conditions, but that the two are subjected to the same conditions and governed by much the same laws of evaporation can not be doubted. Admitting this, the quality of the evaporation under different conditions will be indicated quite as accurately by this instrument as by any potometer or similar device.

(2) The area protected is proportional to the height and density of the windbreak, and the distance to which protection is felt increases with wind velocity. The protection is appreciable for a distance equal to five times the height in the windward direction and fifteen or twenty times the height leeward.

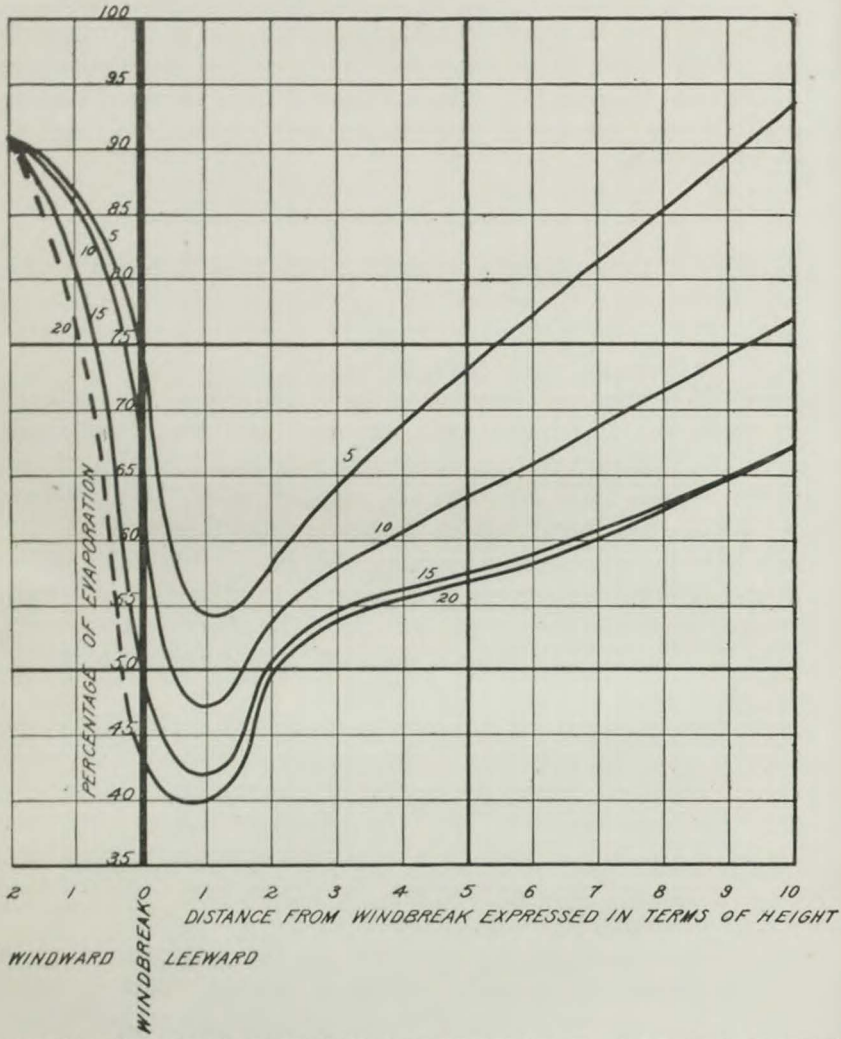

DIAGRAM 16.—Protective efficiency of underplanted cottonwood groves. For wind velocities of 5, 10, 15, and 20 miles per hour. Average height, 75 feet, 70 readings.

(3) The distance from the windbreak of the area of greatest protection depends upon the position of the mass of foilage which affords the protection. With a dense grove, it is immediately in the lee of the trees; with a narrow belt of trees that lack lower branches, it may be as far from the trees as five times their height, and it moves outward as the velocity of the wind increases.

(4) If a windbreak is dense enough to resist the strongest wind, the protection which it gives to any point in its lee increases with an increase in wind velocity. In the case of a moderately dense windbreak, the efficiency remains about the same under all conditions, because the leakage through the windbreak is about the same pro-

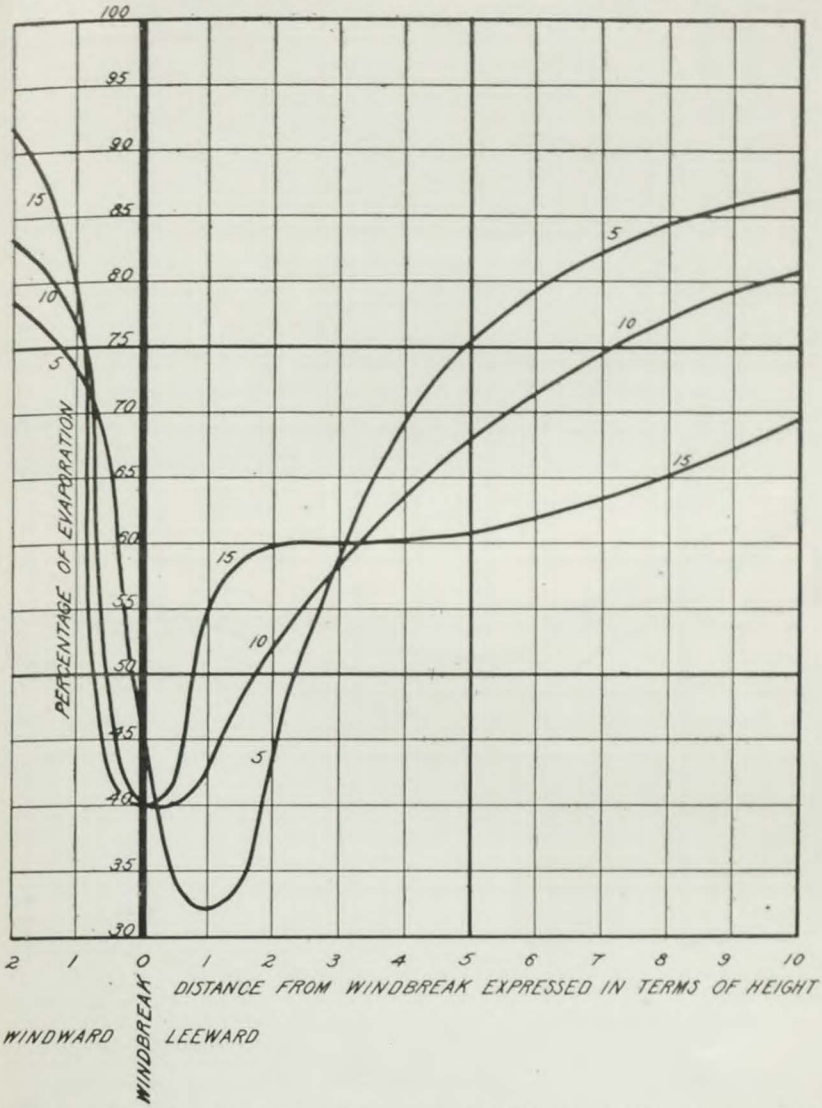

DIAGRAM 17.—Protective efficiency of white pine belt. For wind velocities of 5, 10, and 15 miles per hour. Height, 20 feet; width, 25 feet; 50 readings.

portion of the total amount of wind. With a very open windbreak, the efficiency decreases with an increase in wind velocity.

The final test of a windbreak is the point in wind velocity at which it reaches its greatest efficiency. Of the windbreaks examined, the

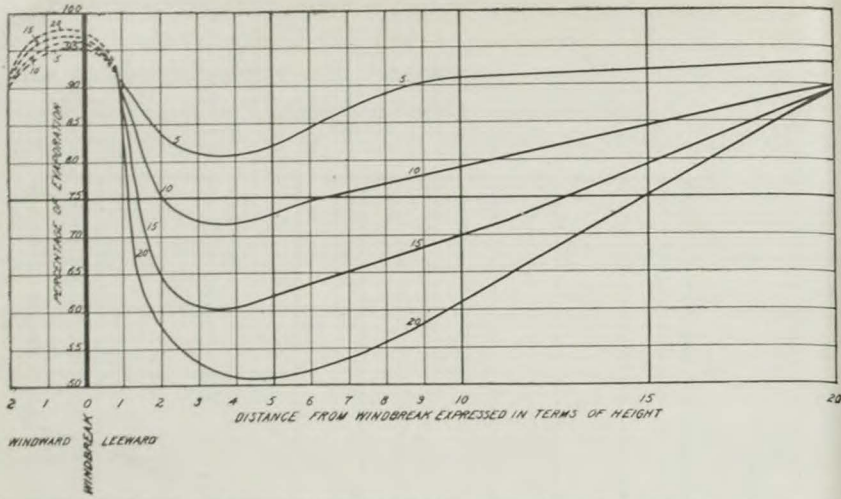

DIAGRAM 18.—Protective efficiency of cottonwood row. Natural density. For wind velocities of 5, 10, 15, and 20 miles per hour. Average height, 50 feet; 100 readings.

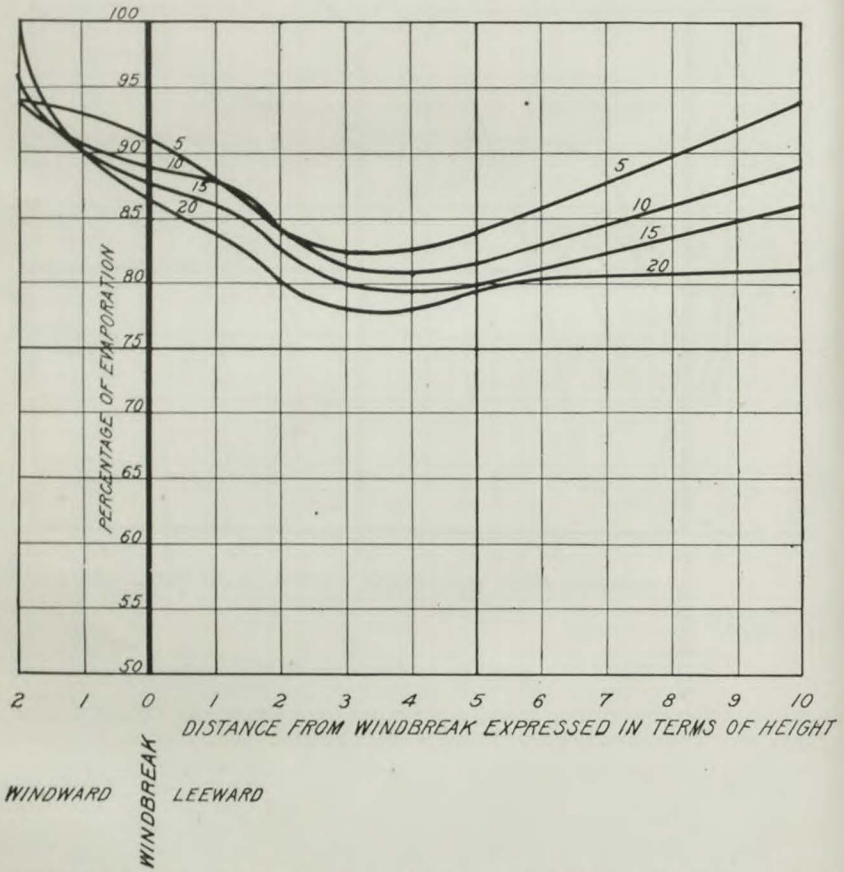

DIAGRAM 19.—Protective efficiency of cottonwood belt. For wind velocities of 5, 10, 15, and 20 miles per hour. Height, 70 feet; width, 100 feet; 83 readings.

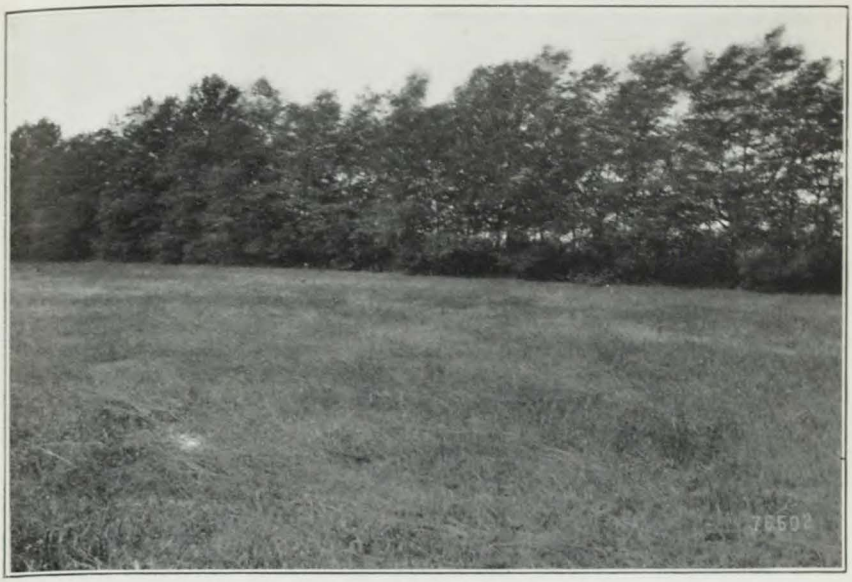

FIG. 1.—THE HEDGE OF HONEY LOCUST IS VERY LOOSE AND OPEN.

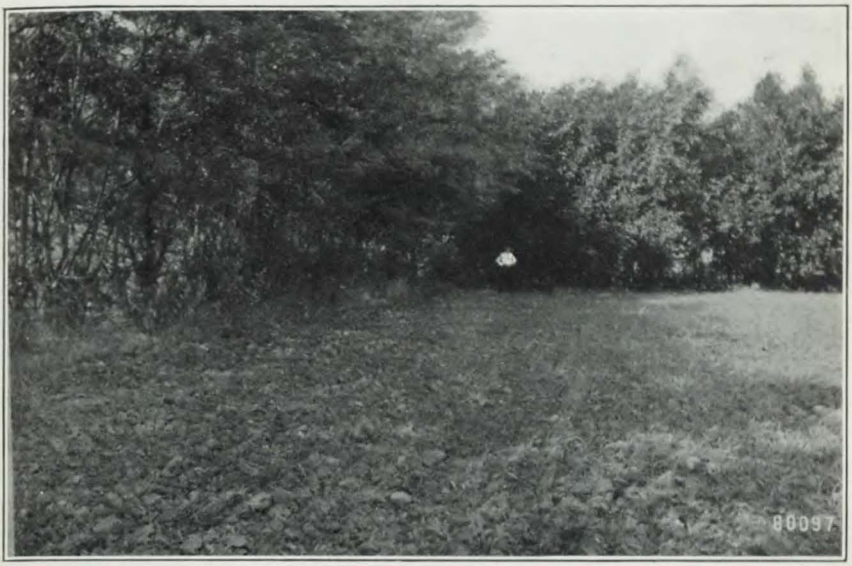

FIG. 2.—ON THE LEFT, HONEY LOCUST; ON THE RIGHT, OSAGE ORANGE. COMPARE DENSITIES.

dense grove of cottonwoods, the belt of coniferous trees, the dense hedge of osage orange, the mulberry hedge, the single row of cottonwood when growing with its greatest density and when reinforced with ash are all to be classed as efficient windbreaks; the belt of cottonwoods and the trimmed osage hedge maintained about the same moderate efficiency to a velocity of 20 miles per hour; the single row of honey locust, though as dense as possible for this species, and the widely spaced row of cottonwoods show a decreasing efficiency with an increase above 5 miles per hour, and can not be considered efficient.

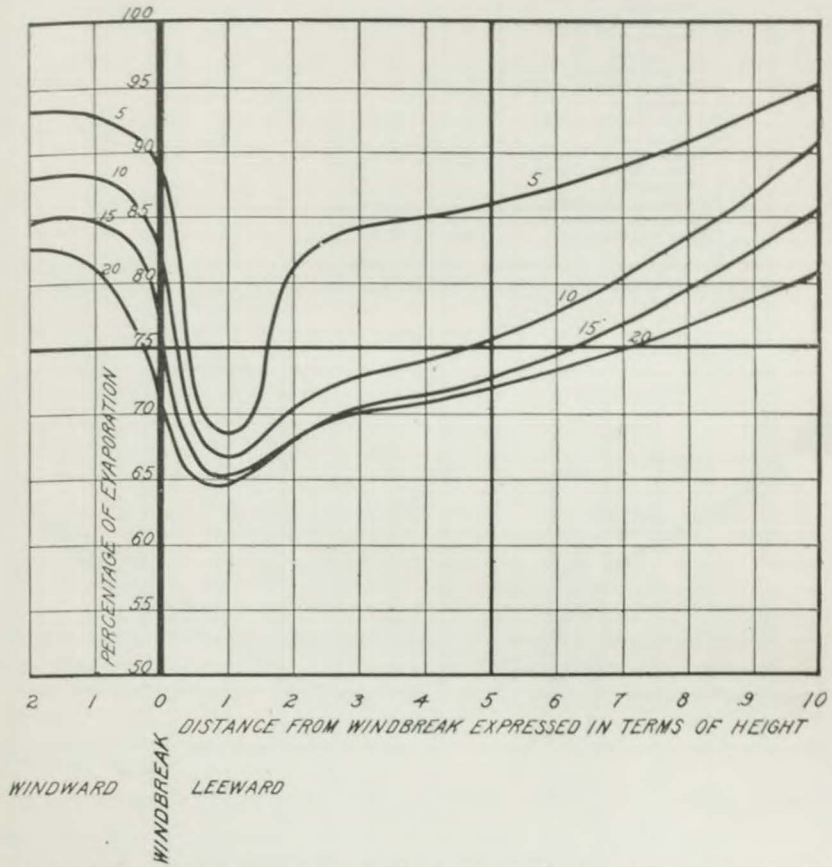

DIAGRAM 20.—Protective efficiency of cottonwood row reinforced with ash. For wind velocities of 5, 10, 15, and 20 miles per hour. Height of cottonwood, 100 feet; ash, 45 feet, 50 readings.

Considering that the zone of economically important protection is between the point 2-ht. windward and the point 10-ht. leeward, the average efficiency over this area, which in the case of a 50-foot windbreak would be 600 feet wide, has been calculated on the basis of each of the curves on diagrams 16 to 24, inclusive. The mean values are given in Table 9.

TABLE 9.—*Mean efficiency of windbreaks in area of greatest protection.*

Diagram No.	Kind of windbreak.	Moisture saved in area twelve times as wide as height of trees at different wind velocities. Miles per hour.				Period of observation.	
		5	10	15	20	Hours.	Month.
		Per ct.	*Per ct.*	*Per ct.*	*Per ct.*		
16	Cottonwood grove (underplanted).	23.3	31.9	38.7	40.1	70	July and September.
17	White-pine belt	31.1	33.3	35.8	.....	50	November.
18	Cottonwood row, natural density.	12.3	18.6	26.6	33.4	100	June, July, August.
19[1]	Cottonwood belt (no low branches).	11.7	13.9	15.5	17.0	83	August, September.
20	Cottonwood row, reinforced with ash.	12.8	20.2	23.7	25.8	50	September.
No diagram	Cottonwood row, widely spaced.	15.1	11.3	.....	.....	13	August.
21[1]	Osage-orange hedge, dense.	21.5	23.2	26.4	.....	173	June, July, August.
22[1]	Osage-orange hedge, open (lower branches trimmed).	26.0	27.2	27.2	27.5	275	Do.
23a	Mulberry, two rows	.....	21.2	.....	.....	16	August.
23b	Mulberry, single row	.....	28.7	.....	.....	6	Do.
24	Honey-locust hedge	29.6	22.9	.....	.....	29	Do.

[1] Results of studies made in cooperation with the Nebraska Agricultural Experiment Station.

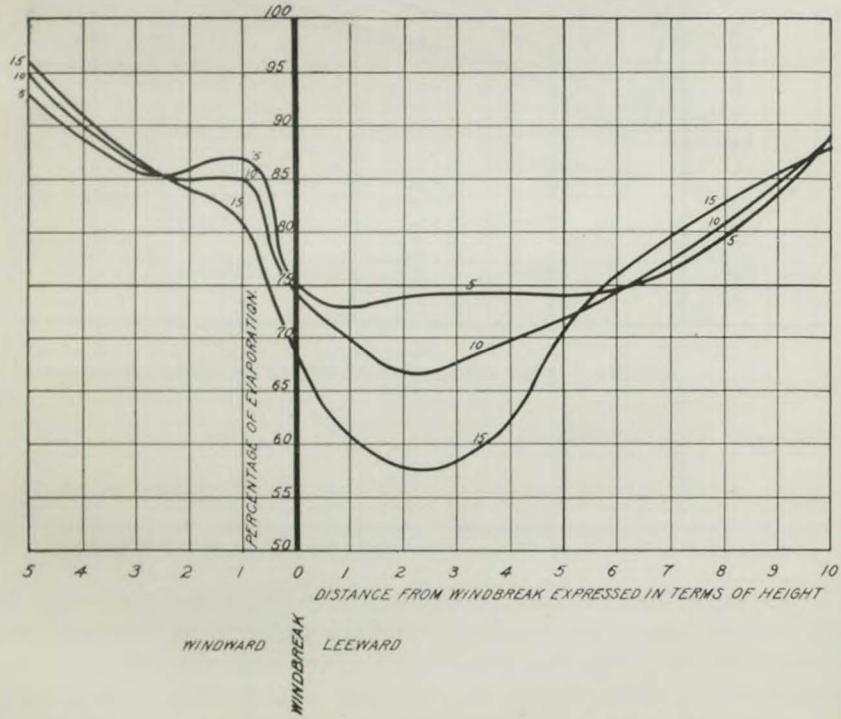

DIAGRAM 21.—Protective efficiency of dense osage orange hedge. For wind velocities of 5, 10, 15, and 20 miles per hour. Average height, 17 inches; 173 readings.

RESULTS OF CHECKING EVAPORATION.

The percentage of evaporation in a field sheltered by a windbreak, as compared with the evaporation in the open, having been calculated, it will be interesting to determine what this may mean quantitatively where the loss of moisture by evaporation is an important item in farm economy.

Observations [1] have shown that the amount of water evaporated from a free water surface in the States of Kansas and Nebraska is between 40 and 50 inches per annum, or about 45 inches for the central

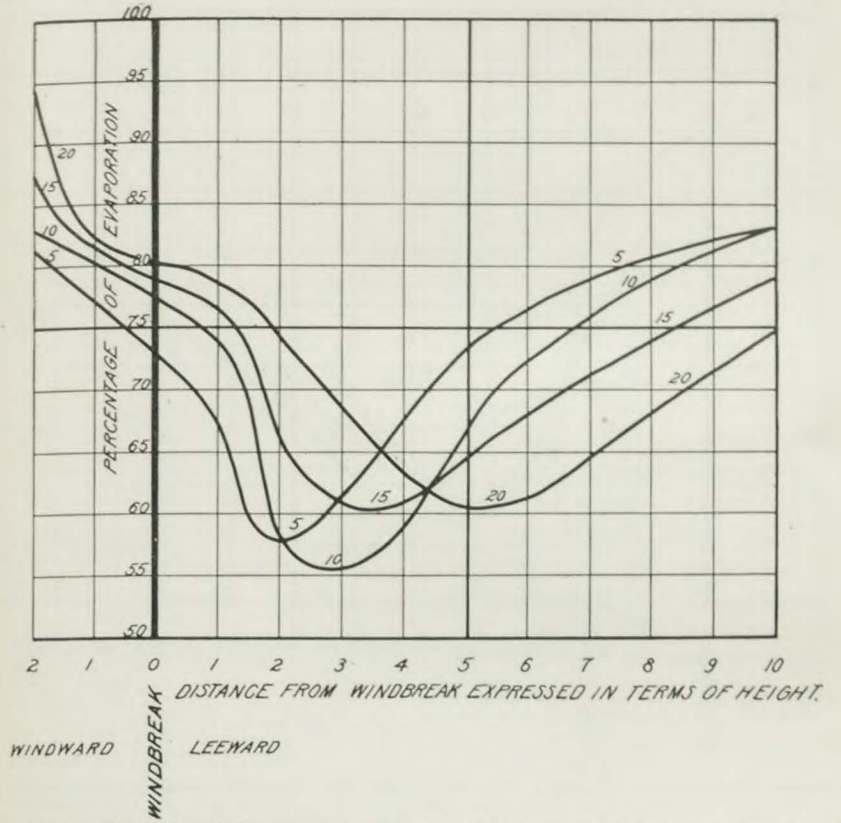

DIAGRAM 22.—Protective efficiency of open osage orange hedge. For wind velocities of 5, 10, 15, and 20 miles per hour. Height, 23 feet; 275 readings.

portion of those States. The amount evaporating during the growing period for corn, May to October inclusive, is about 73 per cent of the total, or 33 inches. It has also been computed that the evaporation from a field of grain is about 1.7 times as great as that from a free water surface,[2] or, in the case in question, 56 inches. This probably represents the demands of the air for moisture in a region where the

[1] Kimball, H. H., "Evaporation Observations in the United States." Monthly Weather Review, Vol. XXXII (1904), No. 12.

[2] Ebermayer, E., "Die gesammte Lehre der Waldstrev," 1876.

total rainfall for the year is not over 25 inches, and where, therefore, the demand can not be supplied. The result is poor plant growth.

How much better will be the growth of the plants if the evaporation is reduced by the presence of a good windbreak to 50, or even 40, per cent of the normal amount? The 28 inches, then, demanded from the field crop will be scarcely more than the annual precipitation. A good windbreak 100 feet high and one-half mile long will reduce by 32 per cent the evaporation from 73 acres, and thus decrease the possible loss of moisture from 56 inches to 39 inches, where the mean

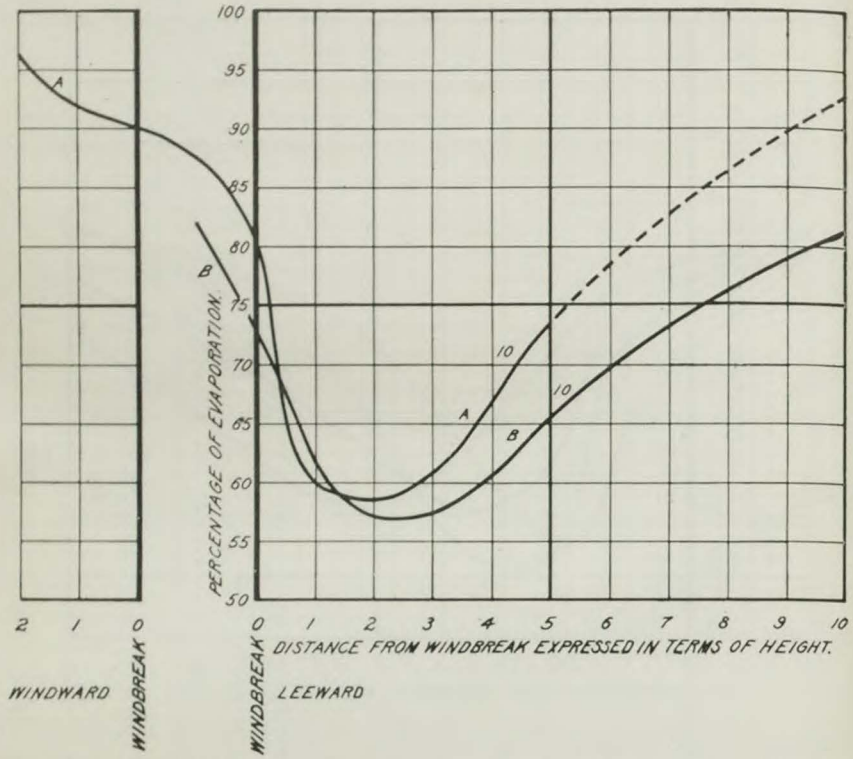

DIAGRAM 23.—Protective efficiency of mulberry hedge. For wind velocities of 10 miles per hour. A, two rows, road between, height 24 feet; 16 readings. B, single row, height 32 feet; 6 readings.

wind velocity is 10 miles per hour. By such protection the water supply of the field may be retained until long after unprotected fields have become dry.

Relation to crops.—Since the season of 1908 was unusually wet, there was no serious drought damage. In the spring there was a slight drought, which affected sprouting corn and considerably reduced the stand in fields of small grains. The plants which survived, however, later obtained an abundance of moisture, so that a moderate crop was harvested. Corn was not much damaged before the rains arrived, but it is probable that a part of the later-observed

benefits arose during the dry period through the saving of moisture effected by the windbreaks early in the season. The main credit to windbreaks for corn protection in the season of 1908 must be given in connection with heat. In many cases increased heat would damage crops were evaporation not checked at the same time.

Measurements made in two fields of small grain show beyond a doubt that great benefit may be expected from windbreaks in dry

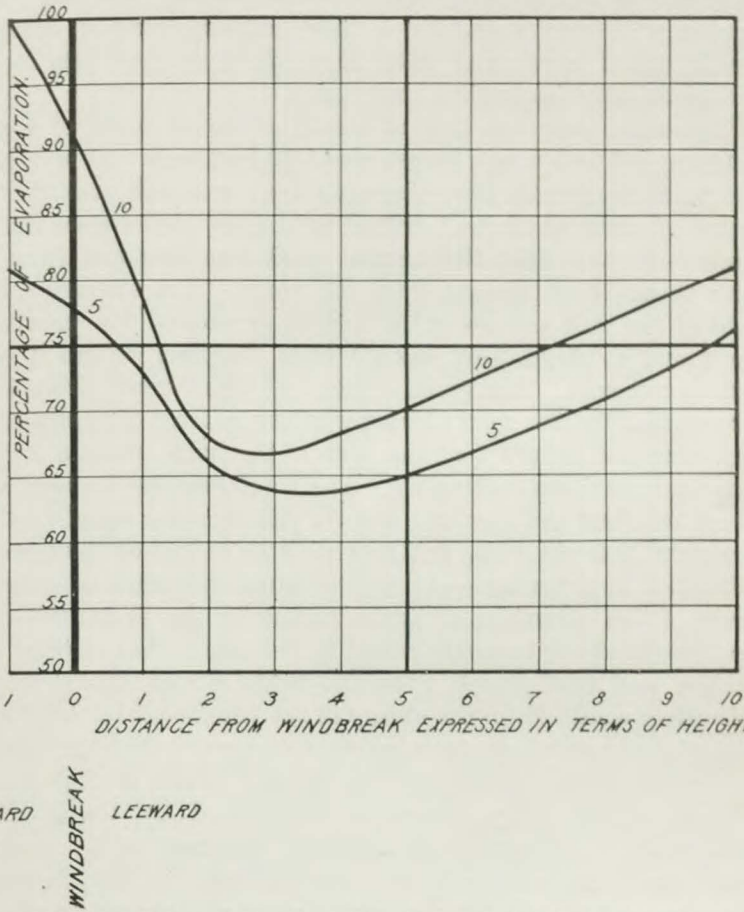

DIAGRAM 24.—Protective efficiency of young honey locust hedge. For wind velocities of from 5 to 10 miles per hour. Height, 30 feet; 29 readings.

seasons through their conservation of moisture. The first case was that of a wheat field partly protected on its south border by a dense grove of honey locust and soft maple. (See diagram 34.) Maple 29 feet high stood next to the wheat. Shading and sapping had caused almost complete loss of crop for a distance of 45 feet from the base of the trees. Immediately beyond this the stand of grain was much better than the normal for the field. Samples of the grain were taken at various points in the shelter of the windbreak, thrashed out

by hand, and weighed carefully. The average yield for the whole field (separator measure) was 15¼ bushels per acre. The greatest yield was found at a distance from the trees equal to two and one-half times their height and was equal to 25.3 bushels per acre, or a gain of 10.1 bushels over the average for the field. At 5-ht. the yield was 16.7 bushels per acre, or 1.5 bushels more than the average. The total gain out to 7-ht. was almost sufficient to offset the damage from shading and sapping, and left a net loss equal to the yield of a strip only 3.3 feet wide. In a more extreme case of drought the benefit would have more than offset the loss from sapping, which had practically reached its limit here.

The second case was that of a field of barley south of a grove of scattered ash and honey locust about 20 feet high. It is quite probable that the ground near the windbreak was well soaked from the effects of snow which had drifted in the lee of the trees during the winter. In this field the normal yield was obtained from sample plots about 10-ht. distant from the grove. The average calculated yield of the field was about 16 bushels per acre. The greatest yield was found at about 3-ht. distant from the trees, where it was 30.6 bushels per acre. The great distance of this "crest" from the trees is explained by the open character of the grove. The effects of sapping were not apparent at the edge of the field, where a strip 5 feet wide had not been cultivated. The total gain in the field was sufficient to offset the loss and leave a net increase equal to the yield of a strip 59.5 feet wide, or 2.98 times the height of the trees.

Relation to irrigation.—At a time when irrigation is occupying so much of the attention of agriculturists in the West the effect of windbreaks upon the water stored in reservoirs, that moving through ditches, and that placed upon the fields is exceedingly important. This effect results from the ability of the windbreak to check evaporation of the water from the time that it reaches the reservoirs to the time when it has soaked into the ground and is available to crops.

Many of the large reservoirs established by the Reclamation Service are in mountainous country, hemmed in by steep walls. Windbreaks are obviously not needed here. A few, however, are in open country and have immense surfaces exposed to the air. A large area of the reservoirs might, in such cases, be protected by windbreaks planted along the borders. The amount of water saved may be roughly calculated per mile of windbreak for a given region.

It has been observed that in the case of the Pische instrument the reduction in the percentage of evaporation is not so great as the reduction of wind velocity. Take, for example, the case of a cottonwood belt (diagrams 15 and 19) which, with a wind velocity of 15 miles, reduces the evaporation at a given point only 20 per cent, while the wind velocity was reduced 46 per cent. Supposing that the

same relation exists over the entire area to the leeward, we have out to 10-ht., in this case, a mean reduction in wind of 35.6 per cent (Table 9) or 9.7 miles per hour as against 15 miles.

Applying these figures, with the aid of Fitzgerald's formula for evaporation $(0.0166\ (e_s - e_d)\ (1 - \frac{V}{2}))$ to a region in which the annual loss of water amounts to 60 inches, we have the evaporation from the reservoir reduced to 41 inches per annum, or a saving of 19 inches, for an area of 60 acres, which would be so protected by a windbreak 1 mile long and 50 feet high. This would be more than enough to irrigate an equal area of cultivated land for an entire season.

Immediately after water has been turned upon fields, and for a few days while the surface soil is saturated, there is chance for great loss by evaporation. The loss during the first few days after flooding may be a very important item in the duty of water reaching the crops.

During parts of June, July, and August, 1908, an experiment was conducted to determine the relation between the loss from a Pische evaporometer, exposing moist filter paper, and another, similarly exposed, supplying water to a shallow dish of sand with the same area as the filter paper. The sand was kept continually saturated. The evaporation from a saturated sand surface was found to be about 60 per cent greater than that from the filter paper, and was equally influenced by an increase in wind velocity. The greatest evaporation for a period of 24 hours, during the observations covering 72 days, was 105.5 cubic centimeters, or a depth over the area exposed of 1.6 centimeters, or 0.63 inch. The average wind during the day was 12.8 miles per hour, and at night 9.1 miles. The mean relative humidity was 74 per cent. These conditions are not at all abnormal for the region of eastern Nebraska where the measurements were taken, and the conditions favorable to evaporation are exceeded very frequently in the dry regions where irrigation is depended on. It may easily be seen, then, that during three days when water was being turned onto a field, and while the surface soil was yet moist, the loss of moisture in unprotected areas might amount to 2 inches or even more. An efficient windbreak, 50 feet high, would reduce this evaporation in a field 30 rods wide to the leeward by at least 30 per cent.

It must not be forgotten that the same conditions exist for a longer or shorter period after each rain in every section of the country.

VI. HEAT.

The effect of a windbreak upon temperatures in the zone of its influence is much greater than is commonly supposed. Just how such effects are brought about and how the measurements of temperatures

have been made, have been explained. The season of 1908 was peculiar in the Middle West, in that the rainfall was excessive and the mean temperatures, because of the unusual amount of cloudy weather, were below normal. Consequently, while it was expected that the benefit arising from windbreaks would be found to be the result of their effect upon evaporation, a careful analysis of the figures indicates that in that season the evaporation was not excessive and that the real benefit from windbreaks came through their ability to affect temperatures. Table 10 gives the climatic data from two Weather Bureau stations in Kansas and Nebraska, and compares 1908 with the average of about 20 earlier years. These figures signify that windbreak effects upon crops in a normal year might be somewhat different from those recorded in 1908, though the measurements of evaporation indicate that an equal amount of benefit may be expected in the driest years.

TABLE 10.—*Wind velocity, precipitation, temperature, and humidity for 1908, as compared with the normal.*

Months	Station at Lincoln, Nebr.							
	Wind.		Precipitation.		Temperature.		Humidity.	
	Normal.	1908	Normal.	1908	Normal.	1908	Normal.	1908
	Miles per hour.	*Miles per hour.*	*Inches.*	*Inches.*	*°F.*	*°F.*	*Per cent.*	*Per cent.*
April	14	13.6	2.6	1.28	52	54.2	54	44
May	11	11.8	4.6	5.35	62	60.5	59	57
June	10	12.0	4.4	11.24	71	69.2	58	63
July	10	8.4	4.1	8.08	76	74.2	54	60
August	9	8.4	3.4	2.84	75	73.2	59	58
September	11	9.5	2.1	.53	66	70.8	56	51
October	11	13.0	2.1	2.34	55	52.8	56	61

Months.	Station at Dodge, Kans.							
	Wind.		Precipitation.		Temperature.		Humidity.	
	Normal.	1908	Normal.	1908	Normal.	1908	Normal.	1908
	Miles per hour.	*Miles per hour.*	*Inches.*	*Inches.*	*°F.*	*°F.*	*Per cent.*	*Per cent.*
April	14	11.2	1.8	1.35	54	55.0	46	48
May	13	12.7	3.2	.90	64	64.0	51	45
June	11	14.3	3.4	8.76	73	71.9	51	55
July	12	8.4	3.2	1.67	78	75.2	48	57
August	11	9.1	2.5	1.51	77	76.0	52	49
September	12	9.0	1.5	1.11	68	70.2	47	49
October	10	11.9	1.5	1.17	56	54.8	50	54

MEASUREMENTS OF AIR TEMPERATURES.

Diagram 25 shows graphically the highest and lowest temperatures measured on both sides of a dense grove and within it when there was a constant wind velocity of from 7 to 8 miles per hour. As in all similar cases, the observed temperature in the open is taken as a nor-

mal, and other temperature lines are shown at intervals of 1° F. above and below this normal. Diagrams 26 and 27 express the summation of temperatures, or the total amount of heat registered at various points relative to the windbreak during the hours of insolation. The summation at each point is expressed as a percentage of the sum of the hourly temperatures in the open, which is taken to be 100 per cent of heat for the day in question. The summations include temperatures from 5° C. or 41° F. upward.[1] The first diagram represents conditions in warm September days; the second, conditions when the temperatures were scarcely above the growing temperature.

Diagrams 28 to 31 show the lowest temperatures recorded on a number of nights, in relation to four classes of windbreaks and under

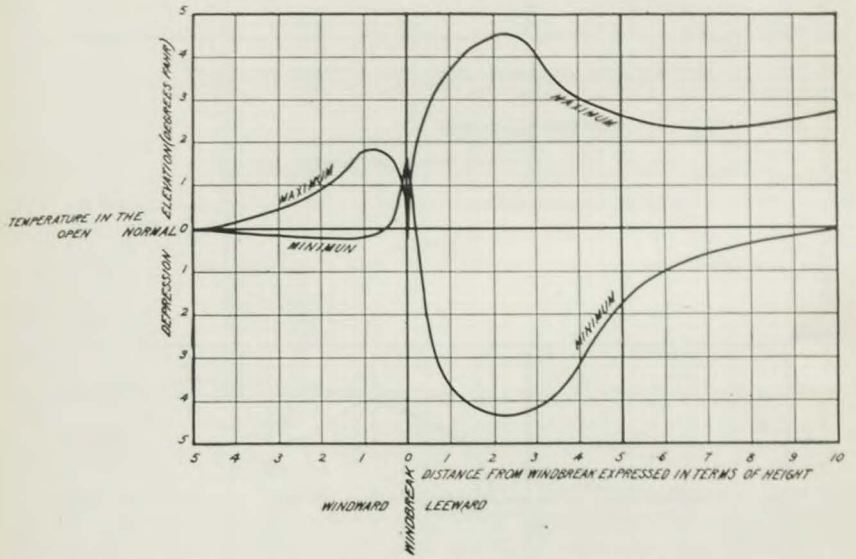

DIAGRAM 25.—Effect of dense groves on daily range of air temperatures, with wind velocities of 7 to 8 miles per hour. Normal maximum temperature 92.3° F.; normal minimum temperature 66.3° F.

various atmospheric conditions. In each case the figure on the curve refers to the probable lowest wind velocity as estimated from the average velocity for the entire night. Some of the results (as *C*, diagram 30) were obtained in cornfields simultaneously with the results obtained in an open field bearing a similar relation to the windbreak.

From a careful study of the results shown in these diagrams the following deductions may be drawn:

(1) Other conditions being equal, both the highest maximum temperature at midday and the lowest minimum temperature at night

[1] According to De Candolle, vegetative growth does not begin until the temperature reaches a height of about 6° C. or 42° F., and a similar basis has been used in all calculations to show the total effect of the windbreak on the possibilities of crop growth.

(diagram 25) are found at the same point relative to the windbreak and exceed about equally (in this case by about 4½° F.) the maximum and minimum temperatures in the open. In other words, the daily range of temperature is nearly 9° F. greater in the protected area than where the air is allowed to circulate freely.

(2) In the zone of windbreak influence the highest temperatures on clear, sunny days, and the lowest temperatures on clear, cool

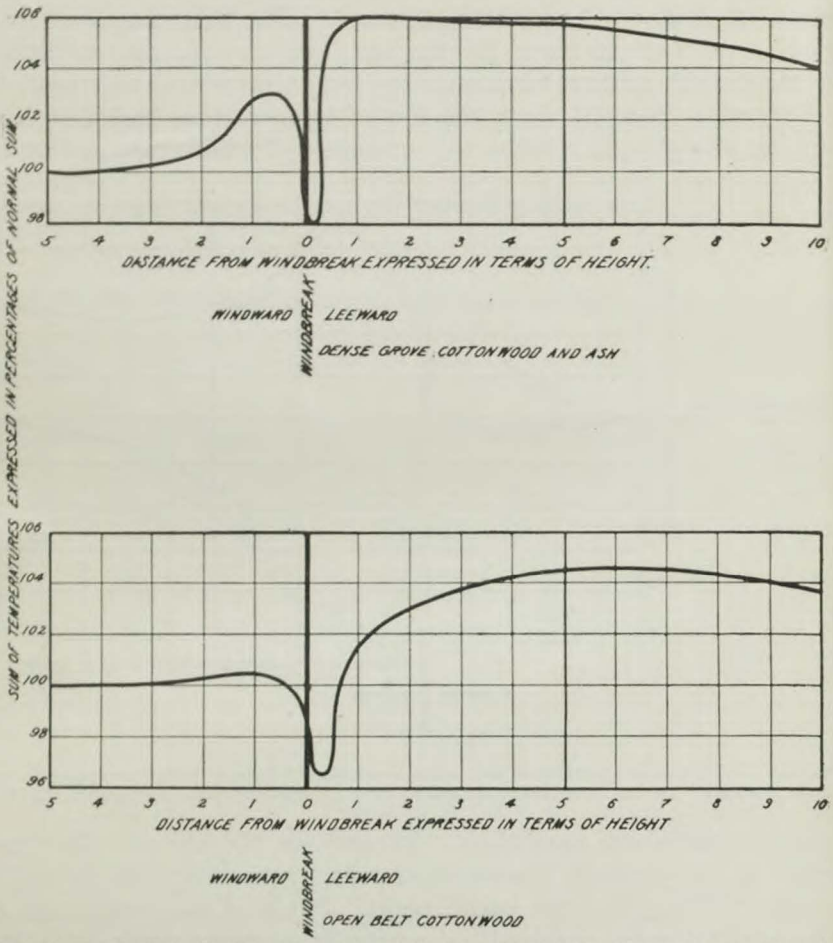

DIAGRAM 26.—Heating efficiency of various windbreaks during hours of sunshine, as shown by summation of temperatures above 5°C. or 41°F. (growing temperature). Thermometers read hourly between 9 a. m. and 5 p. m., midsummer.

nights, correspond in position to the point of greatest windbreak efficiency, as indicated by the evaporation curves (diagrams 16 to 24), which is the point of greatest air stagnation.

(3) Just as the efficiency of a good windbreak increases with the increase of wind velocity in the open, so the degree of superheating in the daytime and of cooling at night, due to stagnation, increases likewise (diagrams 28 and 31).

(4) The most efficient windbreaks from the standpoint of protection will have the most marked effect on the superheating and cooling of the air.

(5) As might be expected, clouds, by preventing insolation, and serving as a blanket at the time of radiation, reduce the effect of the

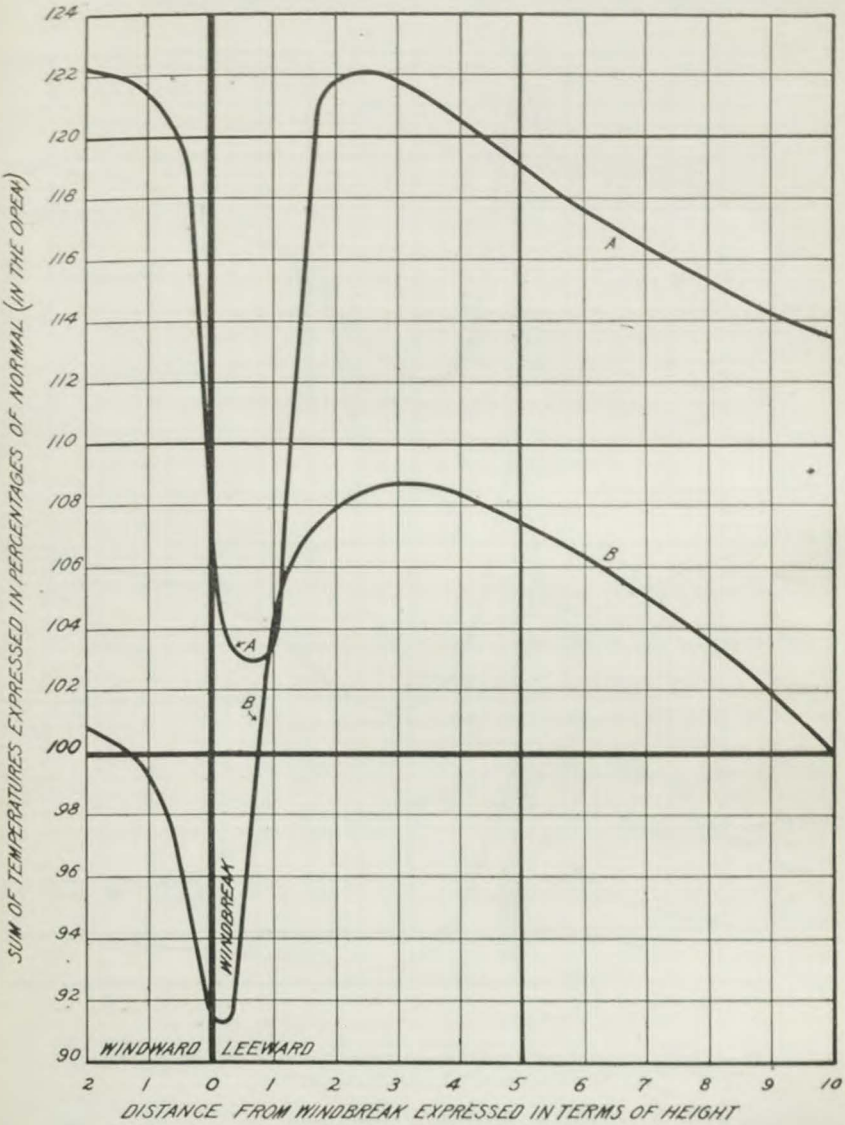

DIAGRAM 27.—Heating efficiency of white pine belt during hours of sunshine, as shown by summation of temperatures above 5°C. or 41°F. (growing temperature). Thermometers read hourly between 9 a. m. and 5 p. m., late autumn. A—with clear sky; B—with cloudy sky.

windbreak (diagram 30). When neither insolation nor radiation is perceptible, as after several days of cloudiness, the windbreak has no effect upon air temperatures. On cloudy days the thermometer

registers no difference in the temperatures within and without the zone of windbreak influence. (See discussion of "Sensible temperatures.")

(6) The warmth collected in and under the trees will be appreciable at night for a short distance on both sides of the windbreak, unless rapidly diffused by a high wind. The amount of warmth so collected,

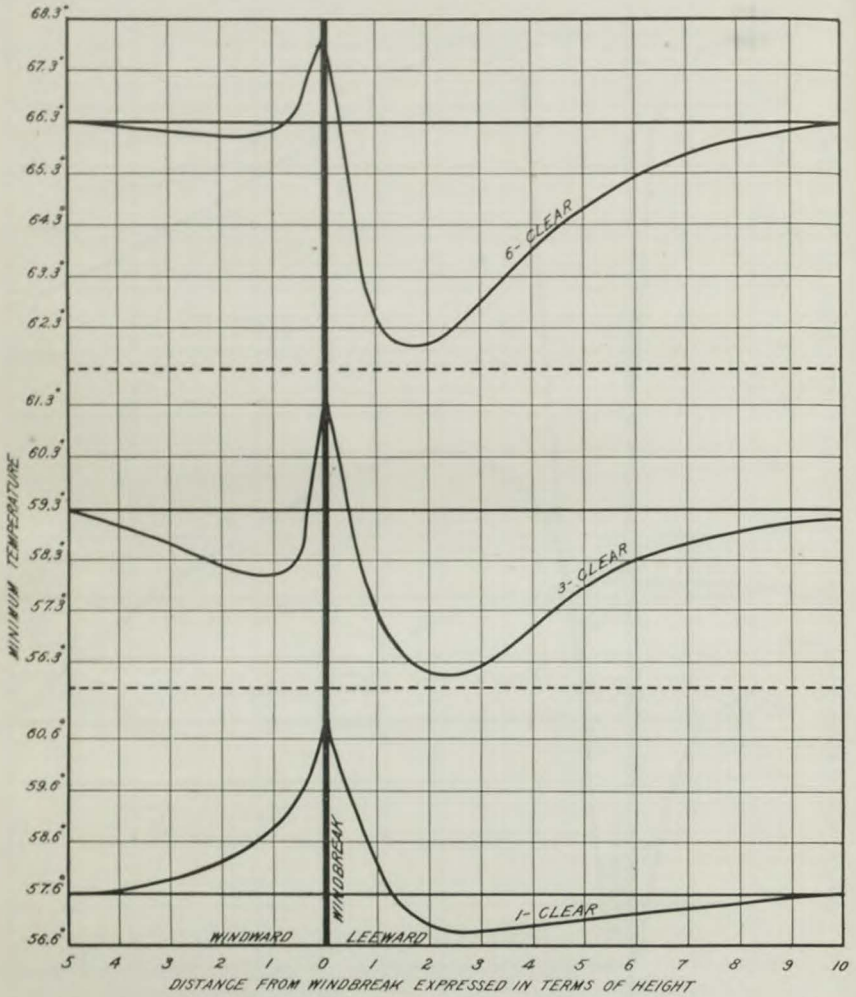

DIAGRAM 28.—Influence of dense grove (cottonwood and ash) on nocturnal cooling of air. With wind velocities of 6, 3, and 1 miles per hour.

and the extent of its measurable influence, will increase with the width and area of the windbreak.

(7) During precipitation, the effect of the windbreak is beneficial because it checks the velocity of the wind which gives a penetrative force to the particles of moisture, and which also causes excessive cooling by evaporation from the moistened surfaces. This checking

of evaporation is appreciable even in the minimum temperatures as registered by thermometers which expose only a very small surface to the wind; it would be even more marked with thin objects like leaves which have a very large surface in proportion to their volume.

(8) It is *probable* that the effect of a windbreak at night is always beneficial in checking evaporation from and cooling of leaves in the protected zone.

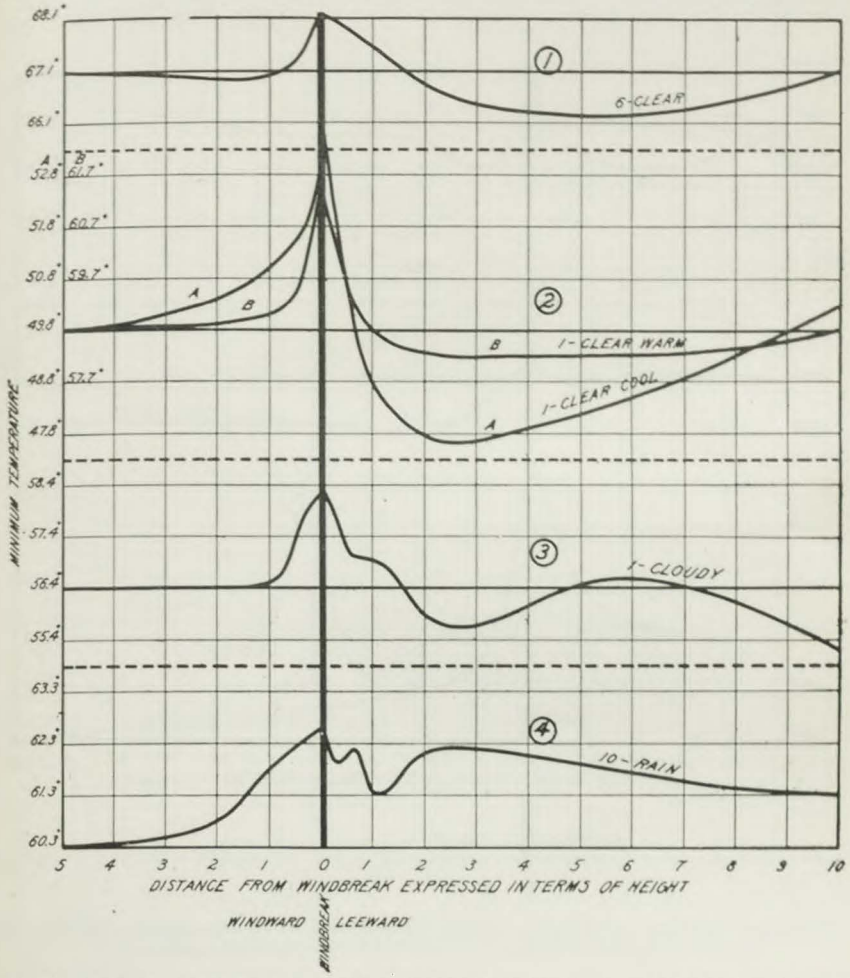

DIAGRAM 29.—Influence of cottonwood belt on nocturnal cooling of air, under various conditions of sky and wind movement. Wind in miles per hour; temperature in degrees F.

(9) The daily superheating of the air amounts to about the same number of degrees whether the temperature outside the protected zone be high or low, but as expressed in percentages of the total heat available for plant growth, it is most important in the spring and fall, when the supply is lowest. (See diagrams 26 and 27.)

Obviously, the heating of the air in the protected zone will increase its capacity for moisture, and this will in part counteract the reduction of evaporation due to the checking of wind. But the effect of superheating will never equal that of the reduction of wind velocity.

MEASUREMENTS OF SOIL TEMPERATURES.

A study of the effect of windbreaks upon soil temperatures leads to exactly the conclusions that have been drawn from the study of

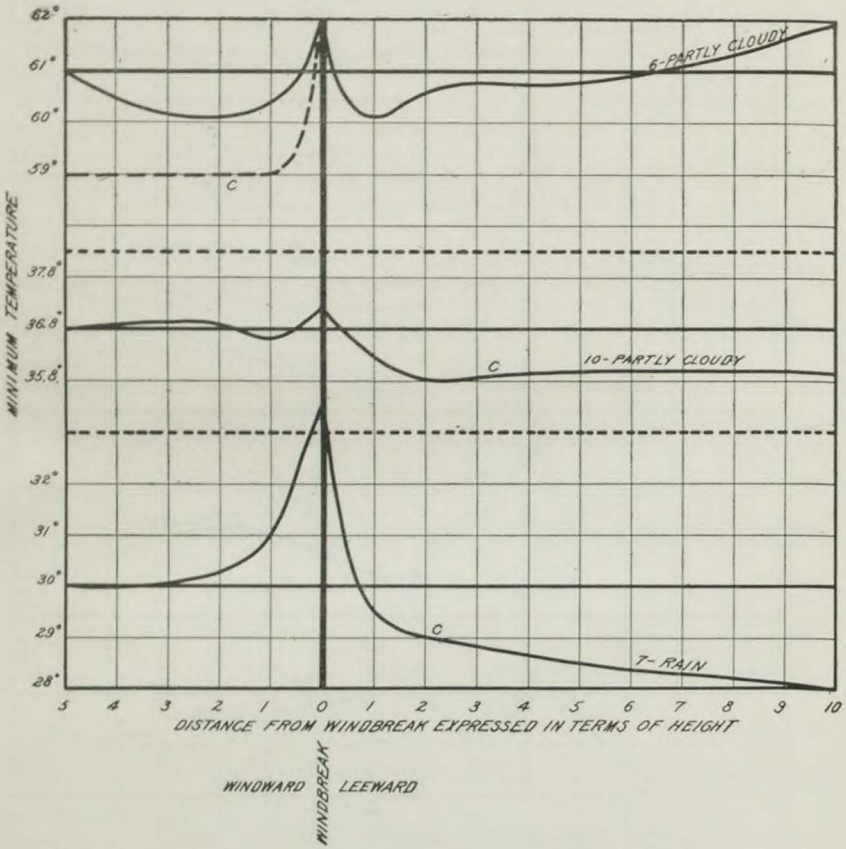

DIAGRAM 30.—Influence of cottonwood row (reinforced with ash) on nocturnal cooling of air in cornfield and unplanted fields. Temperature lines in cornfield marked "C."

their effects upon air temperatures. In addition, however, there is the effect of shade on the ground in the immediate neighborhood of the trees; whereas the effect of shade upon rapidly moving air currents is barely appreciable.

Studies have been made of the temperature of the soil at a depth of 20 inches (5 decimeters), which is probably about the mean maximum depth of the roots of annual crops. Nearer to the surface the conditions are probably very similar to those of the atmosphere.

Throughout the period, June 17 till August 5, the relation of temperatures at various points in the zone of windbreak influence remained constant. In the zone of perpetual shade there was an area in which soil temperature was low. This extended to ½-ht., north, where shadow fell only during part of the day. Immediately beyond this the temperature of the soil was higher than in the open. The highest soil temperature was recorded at 2-ht. north, which corresponds to the point of maximum windbreak efficiency and to

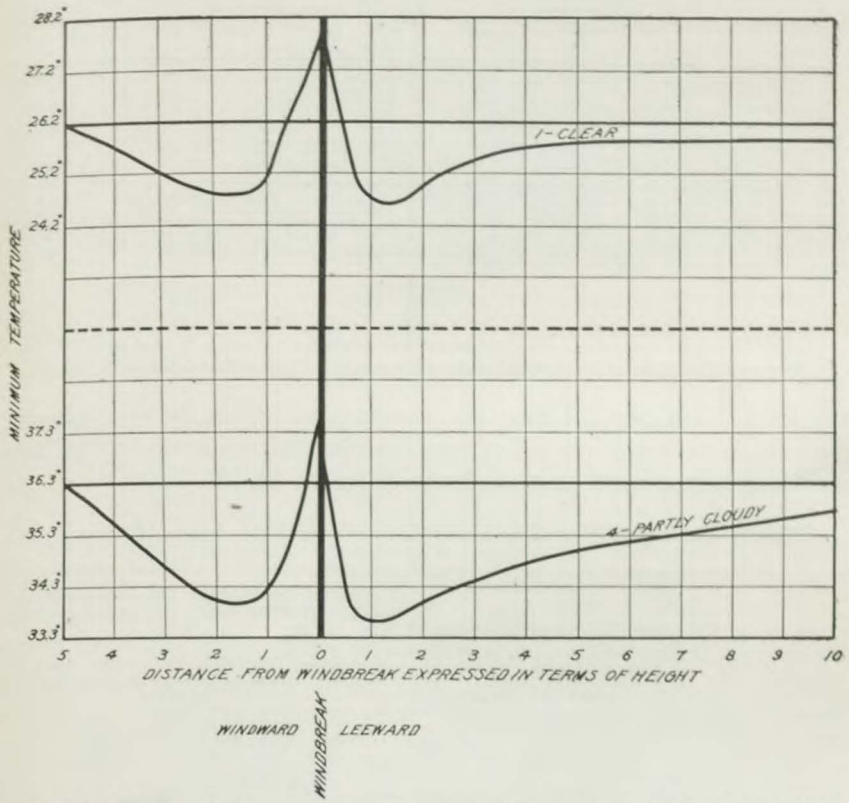

DIAGRAM 31.—Influence of white pine belt on nocturnal cooling of air, with wind velocities of 1 to 4 miles per hour.

the point where the air temperatures are highest in the daytime and lowest at night.

This, it must be remembered, was the relation existing during the period when the temperature was constantly increasing.

On the other hand, when the ground is radiating, in the autumn, the relation of temperatures in the sheltered and unsheltered areas is reversed. Moving air, having retained its warmth longer than the surface of the earth, is then constantly bringing new supplies of heat. Stagnant air, however, imparts no heat to the surface over which it is standing, but, on the contrary, is soon cooled to the tempera-

ture of the ground surface. Hence at this season the air and the soil of a protected zone are cooler than they are in the open, while under the trees radiation is retarded and the temperature is higher than in the open.

Table 11 presents in the first two columns the average of 17 daily readings of soil temperature during the period of increasing warmth,

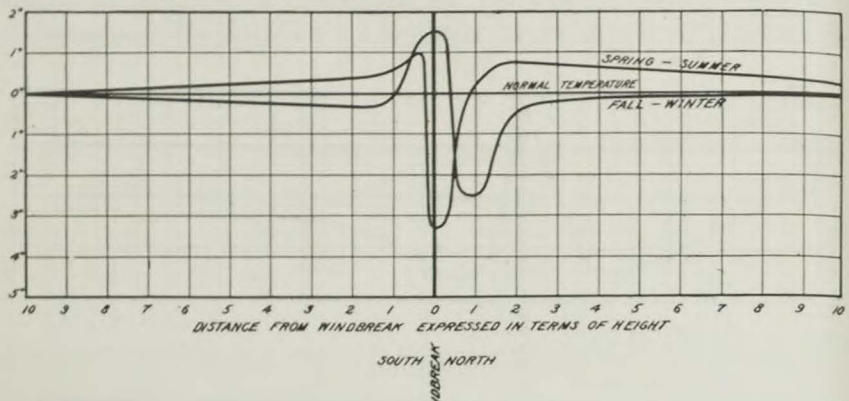
SPRING - SUMMER
NORMAL TEMPERATURE
FALL - WINTER
10 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10
DISTANCE FROM WINDBREAK EXPRESSED IN TERMS OF HEIGHT
SOUTH
NORTH
WINDBREAK

DIAGRAM 32.—Effect of dense windbreak on temperature of the soil at depth of 20 inches

and in the last two columns the averages of 13 hourly readings during two days in the period of rapid cooling of the earth. The same results are expressed graphically in diagram 32.

TABLE 11.—*Effect of windbreak on soil temperatures at a depth of 20 inches.*

Position with respect to windbreak (wind from south).	Soil temperatures during period of increase.[1]		Soil temperatures during period of cooling.	
	Actual temperature.	Variation from open.	Actual temperature.	Variation from open.
South:	° C.	° C.	° C.	° C.
10 height	21.98	0.00	0.00	0.00
5 height			4.14	− .51
2 height	22.35	+ .37	4.63	− .02
1½ height			4.28	− .37
1 height	22.52	+ .54	4.63	− .02
½ height	22.94	+ .96	5.73	+1.08
Under trees	18.66	−3.32	6.17	+1.52
North:				
½ height	20.50	−1.48	2.79	−1.86
1 height	22.26	+ .28	2.12	−2.53
1½ height			3.49	−1.16
2 height	22.71	+ .73	4.24	− .41
5 height			4.55	− .10
10 height	22.26	+ .28		
Open	21.98		4.65	

[1] Results of studies made in cooperation with the Nebraska Agricultural Experiment Station.

The temperature of the ground in the spring and summer is affected by a windbreak as it affects the air temperatures during the hours of insolation; and during fall and winter the effect of the windbreak upon soil temperatures is the same as its effect upon nocturnal air.

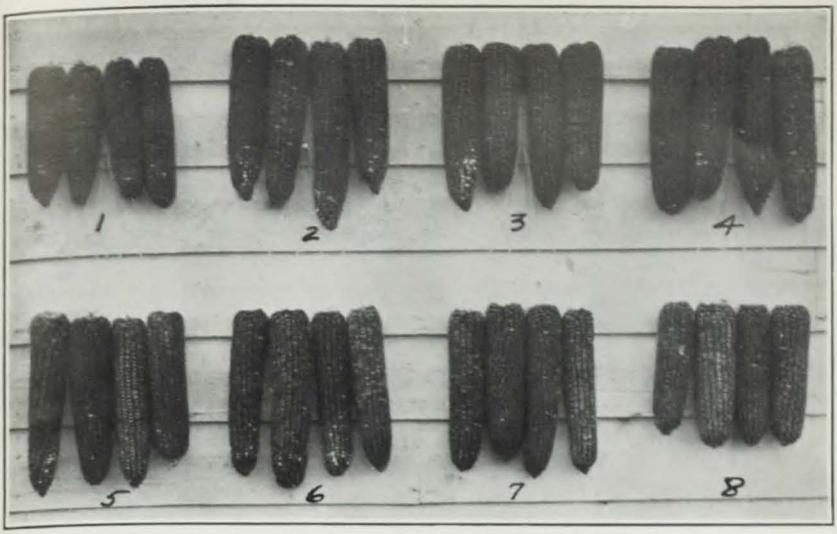

FIG. 1.—EFFECT OF WINDBREAK PROTECTION ON QUALITY OF CORN.

1, In rows shaded by trees; *2-7*, Average maximum ears from protected rows; *8*, Ears from unprotected portion of field.

FIG. 2.—EFFECT OF FAVORABLE ATMOSPHERIC CONDITIONS ON GROWTH OF CORN PLANTS AND YIELD OF FODDER.

On right, in protected zone (weight, 81 pounds); on left, in unprotected zone (weight, 42 pounds)

During most of the growing season the summation of diurnal and nocturnal effects is a positive quantity, since a windbreak conserves the heat of the protected zone. During the late fall and winter the windbreak assists radiation, and a general, more rapid cooling of the soil results in the protected zone.

EFFECTS OF HEATING ON CROPS.

Acceleration of growth and increased yield.—The effect of the superheating of air and soil in the zone protected by a windbreak is favorable to crops which must begin their growth at a time when the heat is barely sufficient for germination, and it probably continues in a decreasing degree throughout the growing season. In other words, a windbreak produces hothouse conditions on a large scale, and since it reduces evaporation at the same time, its total influence is clearly favorable to vegetation. On the other hand, a windbreak may be disadvantageous in spring if a drying out of the soils is desired.

The season of 1908 was especially favorable for noting the effect of heating; it was apparent in cornfields early in the season. The higher temperatures in the protected zone caused earlier germination and more rapid growth than in the open. The following figures on the height of plants in a cornfield to the north of a hedge of osage orange were obtained on July 8 in western Kansas. The height of the hedge was about 20 feet. The spring winds up to that time had been mainly from the south.

TABLE 12.—*Showing effect of windbreak protection in accelerating growth.*

Distance from windbreak.	Height of corn.	Distance from windbreak.	Height of corn.	Distance from windbreak.	Height of corn.	Distance from windbreak.	Height of corn.
Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
9	6.10	39	6.15	69	4.60	99	4.95
19	5.80	49	5.85	79	4.62	150	4.65
29	6.55	59	4.88	89	4.35	200	4.65

A similar cornfield was noted on the north side of a dense, mixed grove in Nebraska. The grove, which was about 38 feet high, formed a complete barrier to the wind. The effects were here even more marked. Late in June the average height of the corn in the first 18 rows next to the windbreak was 4½ feet, while beyond this it was only about 2½ feet. At the close of the growing season the luxuriance of the vegetative growth next to the windbreak was still markedly greater than in the open. At harvesting the weight of the corn at the point of greatest protection was about 18 bushels per acre greater than in the open, or 59 bushels per acre as against 41.

From this point outward the gain diminished, and at 10-ht. it amounted to about 6 bushels per acre. The net gain for the entire area out to 10-ht., including the strip damaged by shading, and calculating for a windbreak 1 mile long, was 423.86 bushels, or 9.22 bushels per acre; that is, as much corn as could be grown on an area as long as the windbreak and as wide as twice the height of the trees. The grove in question was wider than this, but need not have been in order to have furnished almost equal protection. It will, therefore, be seen that the benefit to corn, in this case, paid for all of the ground needed for an efficient windbreak, so that the timber value of the trees was a clear gain to the farmer.

In many other cases the benefit was equally marked on the north side of windbreaks, as shown in Table 13. The gain in bushels has been figured to show the width of strip for which the benefit pays (above all damage from shading). The benefit is about proportional to the density of the windbreak, and the point of greatest benefit corresponds to the crests of heat and evaporation curves. In the case of the dense grove, the crest is very near the trees and just beyond the shading zone.

TABLE 13.—*Showing benefit to corn arising from protection afforded by windbreaks—North side.*

Kind and number of windbreaks.	Average height of windbreak.	Average maximum benefit.		Total benefit expressed as width of strip which windbreak might occupy.
		Yield per acre.	Proportionate distance from windbreak in terms of height.	
	Feet.	*Bushels.*		
7 osage-orange hedges	21.6	16.9	1.87	1.0253×height
1 cottonwood row	60.0	20.5	1.37	1.1783×height
2 shelter belts	29.0	22.8	1.26	1.5625×height
2 dense groves	44.0	25.3	1.22	1.934 ×height

Similar but not so great benefit was measured on the south side of four osage-orange hedges. Other measurements on the south side are lacking, but it is safe to assume that the benefit would be proportionately greater with denser windbreaks. The average of the cases mentioned showed a maximum benefit of 12.11 bushels per acre at 1.99-ht. from the trees, which were 20 feet in height. The net increase out to 10-ht. is equal to the yield of a strip 0.8821 times as wide as the height of the trees. It will, therefore, be seen that the osage-orange hedge, by the benefit on both sides, has brought a net increase in corn yield equal to the yield of a strip 1.9074 times as wide as the height of the trees, in addition to the value of the timber produced. With an osage hedge one-half mile long and 25 feet high, and with corn at 45 bushels per acre and 50 cents per bushel, the increased revenue from the corn would be $65.05.

In only one case was there measureable benefit to corn crops on the east side of north-south windbreaks, and in this case it was offset by the damage from shading. No measureable benefit was noted on the west side of windbreaks. These results were to be expected since the measurements were taken in a region where there is very little wind from either the east or the west. Southwest winds may, to some extent, test the usefulness of the north-south windbreak, but the east winds nearly always occur in cool and cloudy weather.

While the increase of both the weight and size of the ears is marked (see Pl. XV, fig. 1), it is the increased height and luxuriance of the vegetative growth which at once attracts attention (see Pl. XV, fig. 2). As has been said, seed production can not be very greatly increased by improvement of atmospheric conditions alone; the essential chemical elements must be abundantly present in the soil. Fodder production, however, is more dependent upon moisture, light, and heat, and the influences of the windbreak greatly increase the amount of fodder in a field. Fodder is not considered a valuable asset in the Western States, where hay is plentiful, but there are many regions in which it is closely utilized. Table 14 shows the amount and percentage of fodder and grain increase at various points in a cornfield north of a tall cottonwood grove. At the point of greatest growth the increase in fodder and stalk amounts to 95.2 per cent of the normal, while the increase in grain amounts to 37.8 per cent.

TABLE 14.—*Proportionate increase in fodder and grain due to windbreak influence in heating air and soil.*

Distance from windbreak in terms of height.	Weight of ears.		Weight of fodder.		Distance from windbreak in terms of height.	Weight of ears.		Weight of fodder.	
	Pounds per row.	Increase over normal.	Pounds per row.	Increase over normal.		Pounds per row.	Increase over normal.	Pounds per row.	Increase over normal.
		Per cent.		*Per cent.*			*Per cent.*		*Per cent.*
0.73	47.7	None.	42.0	None.	1.40	64.5	35.3	76.2	81.5
1.00	65.2	36.7	56.0	33.3	1.70	62.7	31.5	64.6	53.8
1.20	65.7	37.8	82.0	95.2	2.00	62.9	32.0	62.3	48.4

Wheat and other early grains, because of their smaller heat requirements, do not respond so readily to these more favorable "hothouse" conditions.

Orchards may be affected both favorably and unfavorably by the increased temperatures due to windbreaks. The rapid ripening of the fruit and of the wood of the trees in late summer is just about offset by the danger of accelerating the growth of buds and the blossoms in spring. On the other hand, where warm spring winds, like the Chinook, or where breezes from bodies of water are involved, the effect of the windbreak will be beneficial in spring by preventing this warm air from striking the trees.

EFFECT OF LOW TEMPERATURES.

The lowering of the minimum temperature, and probably also of the mean temperature at night, would partly tend to offset the beneficial superheating in the shelter of the windbreak during the day, especially with such crops as corn, which, when the temperature is propitious, are said to grow as much at night as in the daytime. Diagram 30 shows that the effect of the plants themselves in stagnating the air in a field of mature corn is almost great enough to obliterate the influence of the windbreak on the temperature at 4 feet from the ground, the point at which records were made. On the windward side a uniform temperature more than 1 degree lower than the normal prevailed, while on the leeward side, during a rain, all the temperatures were so much lower as to make the curve appear negative. That positive benefit resulted here, however, is shown by the direction of the curve as it leaves the windbreak, the lowest temperature being at the farthest point where the wind again gained force. But under any circumstances the activity of most plants is very much lessened at night by the absence of sunlight, and the few degrees difference in temperature would have very little effect on most cereals, especially upon wheat, which grows thriftily at the time of the year when the usual night temperature is below freezing. The influence of this depression of the minimum can not, however, be overlooked in the case of orchards, since fruit trees are very susceptible to the least frost, especially at the time of blossoming. A lowering of 4 or 5 degrees in the minimum temperature might mean the difference between a mere chilling of the tender fruit blossoms and actual freezing. On this account orchardists are usually of the opinion that a windbreak is quite as likely to bring damage as benefit to fruit crops. Damage from slight, dry freezing, however, is not apt to lead to a complete loss of the fruit crop, such as occurs when the blossoming trees are subjected to a storm of rain, sleet, or snow accompanied by wind.

The Middle Western States during the season of 1908 furnished a striking example of damage to unprotected orchards. The possibility of a crop in a very large number of unprotected apple orchards was destroyed and the crop in but poorly protected orchards was greatly reduced.

Near David City, Nebr., where the results of the storms at the end of April and the beginning of May were perhaps most severe, there was early promise of an unusually good fruit crop, following a very poor season in 1907. The storm which did the most damage to blossoming fruit trees came from the northwest on the night of April 27, when a wind of about 10 miles an hour was blowing, a small amount of rain and snow fell, and a minimum temperature of 28 degrees was registered at the weather station. At the time there was very little foliage either on the fruit trees or on the forest

trees which in some cases served as a partial protection to the orchards. This storm was followed on the night of April 29 by a brisk northwest wind and a temperature of 31 degrees, but no precipitation. On May 2 a killing frost again occurred with wind from the southeast and a temperature of 26 degrees. On May 6 and 7 there were "clear frosts," with wind in the northeast. The character of these several nights is of special interest in showing that *only the storm from the northwest, which was accompanied by precipitation*, had any marked effect upon the orchard trees.

Throughout Nebraska it was noted during the summer that orchards protected by windbreaks were bearing more heavily than unprotected ones, in many of which there was, in fact, no crop at all. Before the later apple harvest a careful study was made of the orchards in the vicinity of David City, where there are both protected and unprotected orchards growing under otherwise very similar conditions and offering excellent opportunities for comparison.

In wholly unprotected orchards it was found that the trees were bearing little or nothing on the northwest branches and in the exposed tops, though the south and east branches of the same trees were bearing moderately. This indicated that most damage had been done by the storm from the northwest, and that the trees were, in a measure, a shelter for themselves in this storm. Similarly the trees on the exposed north and west sides of the orchard, as a whole, frequently bore less heavily than the parts of the orchard which had had the protection of these trees. Some wholly unprotected orchards, that is, orchards without the protection of taller forest trees, were almost entirely devoid of fruit. Most important of all, none of the trees in orchards well protected by a belt of forest trees showed marked declines from a normal crop. Twenty-eight out of thirty unprotected orchards gave a yield ranging from less than 1 to 3 pecks of apples per tree, though one orchard of this class yielded from 2 to 3 bushels per tree. Partially protected orchards gave an average yield per tree of from one-half bushel to 3 bushels. Five well-protected orchards gave an average yield per tree of 4.9 bushels. Of the latter, one yielded 5.4 bushels per tree and another one 10.9 bushels.

The benefit of a windbreak is here conclusively shown, and there is little need to figure it out in dollars and cents. If the orchard is worth $100 per acre per year, it could easily be shown that the value of a windbreak in such a year as 1908 is at least $80 per acre over a belt ten times as wide as the height of the windbreak.

Storms of the kind described above are not at all unusual in the northern fruit belt; in the Middle West they have occurred several times during the past 10 years at the critical period in the blooming of orchard trees. In fact, any lowering of the temperature at this

season of the year is very likely to be accomplished by precipitation, and it will undoubtedly be found that the influence of the windbreak at the time is beneficial more often, and in a much greater degree, than it is detrimental.

SENSIBLE TEMPERATURES.

It is a well-known fact that the same temperatures as registered by thermometers may very differently affect human comfort owing to differences in the quality of the air, its humidity, or, most of all, its rate of circulation. Low temperatures which cause no discomfort when the air is calm become unbearable when a wind springs up. This is so widely appreciated that windbreaks are, perhaps, chiefly valued for the protection they give against strong winter winds. That there is considerable saving of fuel in heating a house so protected requires no proof, though exact determination of the amount would be difficult. A good windbreak grove may reduce wind velocity as much as 80 or 90 per cent immediately to the leeward, and, at the same time, provide the required fuel without loss of efficiency. If located with due regard for the direction of the prevailing winds, such a grove need not be more than a few acres in extent to serve the double purpose admirably.

Conifers are obviously much superior to deciduous trees where only winter protection is desired. A narrow belt of white pine, consisting of only two rows planted close together and 20 feet high, reduces the wind velocity at 100 feet to leeward by four-fifths. In other words, if a 25-mile wind was blowing the velocity in the shelter of such a windbreak would be only about 5 miles per hour. This reduction in wind velocity is equivalent to a reduction of 19° F. in the cooling effect of the wind upon the skin.[1]

VII. HUMIDITY.

It has been thoroughly demonstrated that large areas of forest appreciably increase the humidity of the atmosphere above them by reason of the excessive transpiration from the trees as compared with that from fields of grain or the evaporation from bare surfaces. This fact, however, is of no economic importance in considering the influences of windbreaks consisting of a row or relatively small body of trees.

A windbreak may more seriously affect the humidity of the air by its disturbing influence upon air currents. The air obtains its moisture by evaporation from the ground and from the plants on the ground. There is more moisture, consequently, near the ground than in the upper strata. A windbreak which deflects the air currents

[1] A French experimenter, Vincent, has calculated that the cooling effect of a wind upon the skin is about 1.2° C. for each increase in wind velocity of 1 meter per second. This, reduced to our terms, is 0.966° F. for each mile per hour increase in wind. (J. Vincent: La Determination de la Temperature Climatologique, Bruzelles, 1890. Reprinted from Annuaire de l'Observatoire Royal pour 1890.)

upward will have little effect upon the humidity of the air in the zone which it protects, except as the stagnation of the air in that zone may permit it to accumulate more than the normal amount of moisture. An inefficient windbreak, however, which permits the wind to pass under the trees, may have a deleterious effect upon the crops in the protected zone by bringing down from the higher strata air which is not saturated to the normal degree. This effect of windbreaks of both classes in deflecting air currents is shown in diagram 33.

The results of an experiment conducted September 7, 1908, as obtained from a large number of psychrometer, anemometer, and evaporometer readings, are given in table 15. A careful study of these figures shows that the wind near the trees on the leeward side was almost as great as in an open situation on the windward side. The lower absolute humidity of the air at this point indicates that the air current measured must have comprised air from a higher stratum mixed with that of the normal surface current. While greater efficiency is obtained at a point some distance from the windbreak, the figures furnish sufficient proof of the undesirability of a windbreak of the open character of the one tested.

TABLE 15.—*Showing the relation of an open windbreak to humidity and other atmospheric factors.*

Station relative to windbreak.	Wind velocity.		Air temperature.	Weight of aqueous vapor per cubic foot.	Vapor deficit in inches mercury.	Evaporation.	
	Per hour.	Per cent of velocity of open.				Amount.	Per cent evaporated of open.
	Miles.		° *C.*	*Grams.*	*Inches.*	*c. c.*	
In the open	11.48	100	29.39	5.474	0.697	18.5	100
2×height to windward			29.58			17.25	93.2
1×height to windward			29.53			16.65	90.0
At windbreak							
1×height to leeward	10.76	93.8	29.49	5.090	.743	17.75	96.0
2×height to leeward			29.81			16.00	86.5
5×height to leeward	7.24	63.0	30.35	5.284	.788	15.00	81.1
10×height to leeward			30.545	5.324	.776	16.70	90.3

On the whole, it must be admitted that the windbreak has no important effect upon the humidity of the air. The reduction of evaporation may be slightly affected by the increased or decreased humidity due to the deflection or stagnation of the air, but will be much more affected in all cases by the reduction of wind velocity.

SUMMATION OF PHYSICAL AND PHYSIOLOGICAL EFFECTS.

A summary of the influences of windbreaks upon the physical factors which affect the growth of plants shows that—

(1) *The zone of competition.*—In a narrow zone or belt adjacent to the trees there is competition which results unfavorably to the annual crops by reason of—

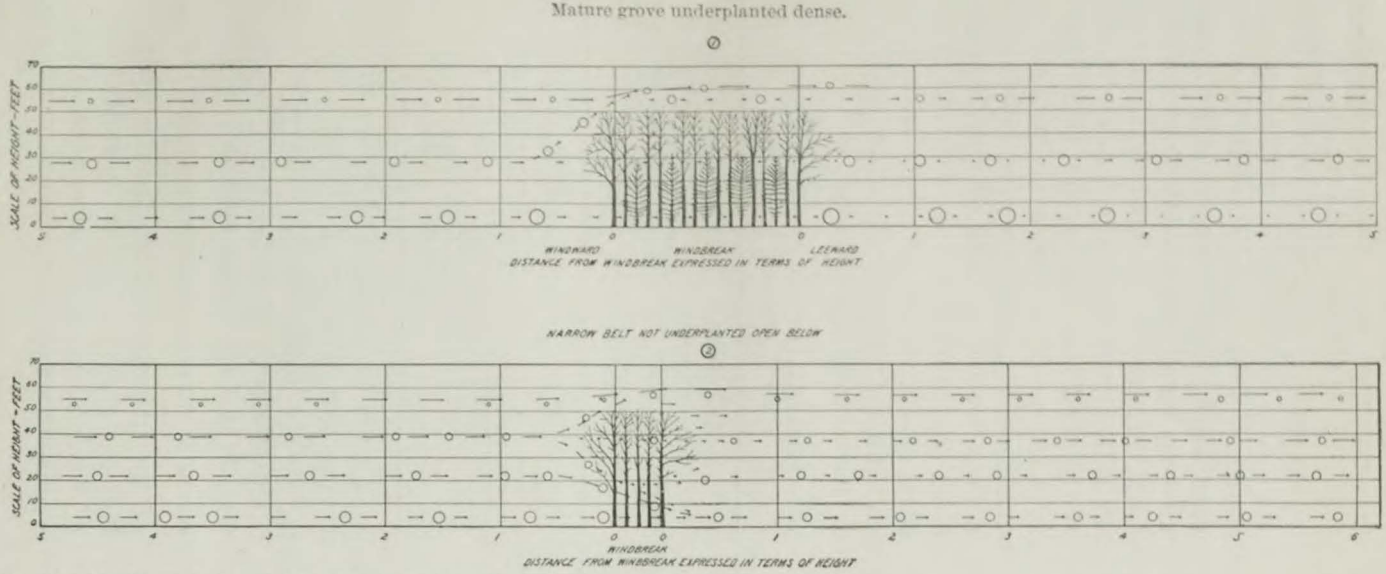
Mature grove underplanted dense.
SCALE OF HEIGHT - FEET
WINDWARD
WINDBREAK
LEEWARD
DISTANCE FROM WINDBREAK EXPRESSED IN TERMS OF HEIGHT
NARROW BELT NOT UNDERPLANTED OPEN BELOW
SCALE OF HEIGHT - FEET
WINDBREAK
DISTANCE FROM WINDBREAK EXPRESSED IN TERMS OF HEIGHT

DIAGRAM 33.—Effect of windbreaks on velocity and humidity of air currents. Velocity indicated by length of arrows; absolute humidity by diameters of circles.

(*a*) Loss of sunlight. This amounts to from 50 to 125 per cent of the light which might fall on an area as wide as the height of the trees. This loss is greatest in the case of north-south windbreaks. It is accompanied by a somewhat greater loss of crops on an area of about the same extent as the shadow, the increase arising from the inability of plants to form seed with a limited amount of light, which might be sufficient for vegetative growth. This shaded area should be utilized for forage crops or for trees which are able to subsist on partial light.

(*b*) Loss of moisture. A zone varying in width from one to five times the height of the trees is affected according to the species and situation. The width of the strip may be greatly reduced by cultivation. This loss of moisture may, in years of drought, result in a complete loss of annual crops in the zone affected. The damage to deep-rooted crops need not be so great.

(*c*) Temporary reduction of soil fertility. This accompanies and is due to the loss of moisture in the root zone.

(2) *The zone of windbreak protection.*—In the wider zone of windbreak influence the protection afforded results in a marked benefit to crops, because of the creation on a large scale of conditions similar to those which obtain in a hothouse. These conditions, all of which result from the ability of the windbreak to check the circulation of air currents, are as follows:

(*a*) Less wind movement. As a result there is less damage by lodging of grain, movement of soils, and uneven drifting of snow.

(*b*) Less evaporation. This results in the ultimate conservation of the moisture of the soil. In dry years this may mean a partial crop instead of a complete loss.

(*c*) Greater heat during the hours of sunshine and lower air temperatures at night. In the aggregate this stimulates plant growth during the spring and summer. The value of this factor in the season of 1908, on the north side alone, was more than sufficient to offset the damage due to shading, and left a net surplus equal to the yield of a strip from one to three times as wide as the height of the trees.

(*d*) Less extreme cold at night, if the windbreak can serve the purpose of checking the evaporation of moisture from objects upon which it falls as rain, sleet, or snow. In such case a benefit to blossoming fruit trees was obtained in 1908 which amounted to as much as 10 bushels per tree in the subsequent crop of apples.

(*e*) A slight increase in the capacity of the air for moisture, because of its greater warmth in the daytime. This increase is not sufficient to increase evaporation where the wind has been checked.

The absolute value of any of these influences will increase with the degree of efficiency of the windbreak, and their total amount on any side of the windbreak will depend upon the direction, velocity, and desiccating power of the prevailing winds (see diagram 34).

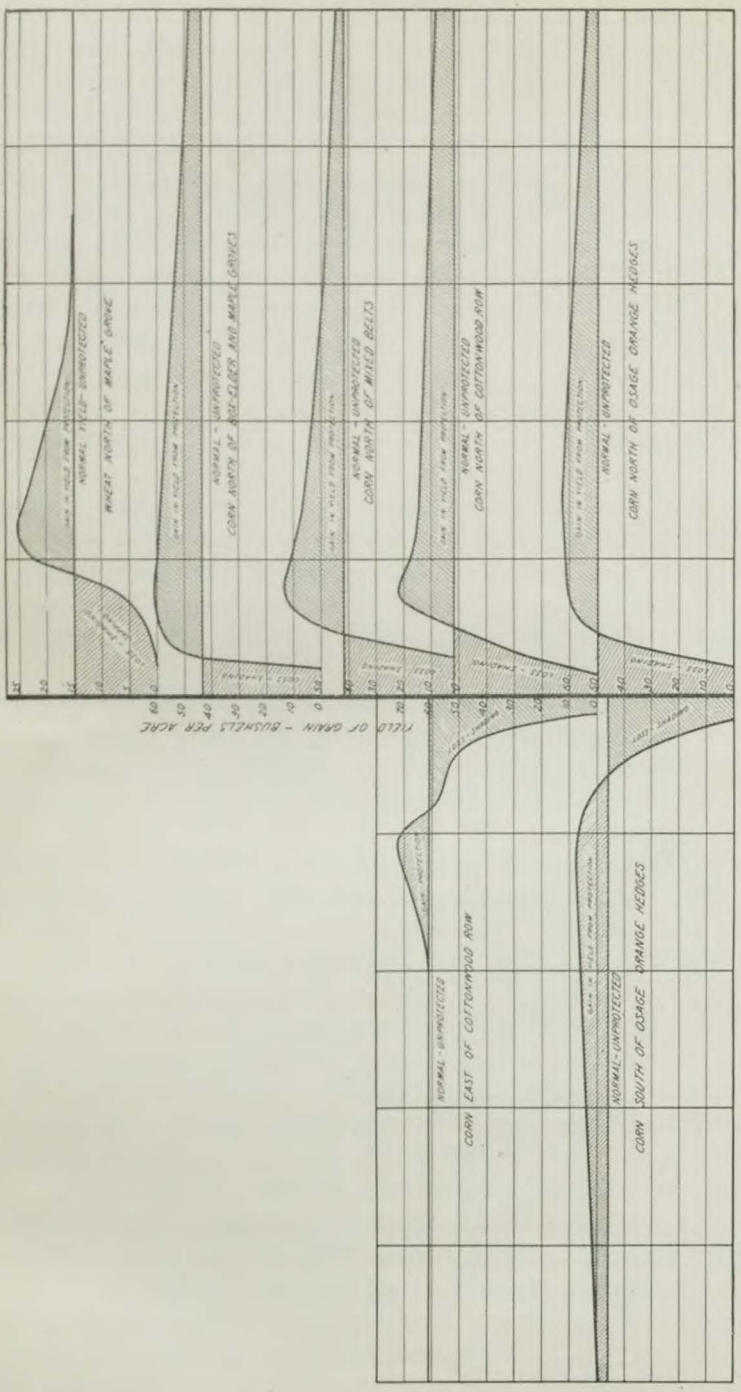
YIELD OF GRAIN - BUSHELS PER ACRE
DISTANCE FROM WINDBREAK EXPRESSED IN TERMS OF HEIGHT
WINDBREAK
NORMAL YIELD - UNPROTECTED
WHEAT NORTH OF MAPLE GROVE
NORMAL - UNPROTECTED
CORN NORTH OF ASH-SILVER AND MAPLE GROVES
NORMAL - UNPROTECTED
CORN NORTH OF MIXED BELTS
NORMAL - UNPROTECTED
CORN NORTH OF COTTONWOOD ROW
NORMAL - UNPROTECTED
CORN NORTH OF OSAGE ORANGE HEDGES
NORMAL - UNPROTECTED
CORN EAST OF COTTONWOOD ROW
NORMAL - UNPROTECTED
CORN SOUTH OF OSAGE ORANGE HEDGES

DIAGRAM 34.—Summation of windbreak influences as shown by yield of crops in Kansas and Nebraska, 1908.

PART III.

DIRECT RESULTS OF WINDBREAK PLANTING—TIMBER YIELDS.

RELATION OF WINDBREAK FORMATION TO QUALITY PRODUCTION.

Before deciding what is the best form for a windbreak, the actual timber value of the available species, and the comparative value of the timber produced in single rows, in belts, and in wider tracts should be carefully measured. A large number of estimates of the products of different species under various conditions have been made with such comparisons in view.

Quality production in the case of the best forest trees depends primarily upon the length of rotation or length of time taken to mature the forest crop. In the production of any forest crop a point is sooner or later reached where the interest on the investment becomes greater than the annual increase in value. This stage, which is known as the "financial rotation," is often reached before the forest has reached its greatest value, especially with species whose value is dependent on the large size and clear quality of the logs. The financial rotation is, of course, reached earliest when the interest on money is high.

The measurements of indirect benefits through protection must have an important bearing upon the profits from forest planting, and especially upon the growing of valuable forest products in long rotations. If the indirect benefits pay the first cost of planting, or at least the interest thereon, an important item of economy is added to the management of woodlots.

The method of planting—whether in rows, belts, or groves—will have a strong influence on the quality and value of the products. Trees in rows, like trees standing alone in open fields, will put a large amount of their growing power into branches. Trees in belts may grow in somewhat better form than those in rows, but if a belt is composed of only two or three rows the trees tend decidedly to spread in both directions. This tendency results in the production of large branches on one side, and frequently of stems which are bent, especially at the base of the tree, where the most valuable timber might be produced. Trees in a grove or forest put most of their growth into the bole; their branches are small and gradually drop off from the base of the tree.

DIAGRAM 34.—Summation of windbreak influences as shown by yield of crops in Kansas and Nebraska, 1908.

In the following estimates of timber products distinction is made between groves in which close competition between the trees existed and narrow belts or rows in which the trees had free access to light and unlimited root space on at least one side.

CALCULATION OF AREA CHARGEABLE TO WINDBREAKS.

In many instances estimates in groves and wide belts were made only for the inside rows, because they alone were growing under true forest condition. It is not difficult to calculate the actual area which such trees occupy. With narrow belts and single rows, however, allowance must be made for all of the space occupied by the branches. As far as possible the figures in Table 3 have been used for this purpose.

Since damage to corn is, on the whole, the least marked the calculation of acreage necessarily chargeable to single-row windbreaks is in most cases based on the greatest damage which results to cornfields. This represents only the area shaded by the trees, and not the area in which damage from sapping might be felt in very dry years.

The area chargeable to a row of trees on account of damage to crops is about proportional to the height of the trees. But the row can not be charged with this area for all of the years the trees have been growing. On an average, approximately one-half of the area has been damaged during the whole life of the trees, though, to be safely conservative, the factor of three-fifths has been used. This estimate is amply liberal, because damage during the first few years was very slight. The debt of the trees was at first small and the interest carried through the full period of years was much less than that from damage done in later years. A comparison with equal annuities from field crops is, therefore, not quite fair to the trees.

The following is the equation for determining the acreage occupied by a row of trees a mile long, when A represents acreage and CF the factor of loss to corn as expressed in percentages of the height of trees, H:

$$(1) \qquad A = \frac{CF \times H \times \frac{3}{5} \times 5280}{43560}$$

When the acreage must be figured from a shading factor, SF, the equation becomes—

$$(2) \qquad A = \frac{SF \times \frac{3}{2} \times H \times \frac{3}{5} \times 5280}{43560}$$

If the acreage occupied by a belt is to be calculated, the distance D, between the outside rows must be added. The equation then becomes—

$$(3) \qquad A = \frac{(D + CF \times H \times \frac{3}{5}) \times 5280}{43560}$$

The shading factor and the resulting damage to crops are usually greater with north-south windbreaks than with east-west ones.

MARKET VALUES OF TIMBERS.

If the value of the timber in the windbreak is to be compared with the value of field crops as based on market prices, the cost of harvesting the crops need not be considered, since it may be assumed that the cost is approximately the same for forest and field crops. Since, however, the major portion of the forest crop, and particularly posts, will be utilized on the farm, the expense of hauling these forest products to market would be saved.

Cottonwood or other saw stuff may usually be disposed of at a net stumpage price. The stumpage value of $10 per M, b. m., which has been placed upon cottonwood lumber is probably too low to represent fairly a comparison with field crops; but since this price may not always be obtained it is perhaps the safest to use. The value placed upon cottonwood and maple fuel ($2 per cord) is also decidedly low when it is considered that a large share of the material will be used on the farm without the expense of a long haul.

In assigning values to fence posts of the different species it has been attempted to construct a just scale based upon the strength and durability of each and to compare the native-grown products with the imported products, such as cedar, which are sold in the lumber yards. The figures given in Table 16 may be a trifle high for Iowa and Minnesota, where native timber is close at hand, but they are correspondingly low for the treeless States of Kansas and Nebraska.

TABLE 16.—*Average values for fence posts—Kansas, Nebraska, Iowa, and Minnesota.*

Species.	Value per post.			
	Class I.	Class II.	Class III.	Class IV (stakes).
Cottonwood	$0.10	$0.08	$0.05	$0.02
Willow	.11	.08	.05	.02
Green ash	.16	.12	.08	.03
Honey locust	.16	.12	.09	.04
Black locust	.22	.17	.12	.05
Osage orange	.24	.18	.12	.06
Russian mulberry	.20	.16	.08	.03
Soft maple	.12	.09	.05	.02
Catalpa	.20	.15	.08	.03

The posts have been classified according to the following specifications: Class I—Length, 7 feet; 4 inches at small end, round, or 3½ quartered; free from crooks. Class II—Length, 7 feet; 3 inches at small end if straight, or proportionately larger if moderately crooked; bad crooks culled to thirds. Class III—Length, 7 feet; 2 inches at small end if straight, or proportionately larger if crooked. Class IV (stakes)—Length, 5 feet; 1½ inches at small end; free from bad crooks which would prevent driving.

ESTIMATES AND DISCUSSION OF SPECIES.

COTTONWOOD.

Cottonwood is not a long-lived tree, but grows very rapidly when young, so that at the end of a few years it yields a good rental in fuel. The lumber from cottonwood is relatively much more valuable, but can not be harvested profitably until the tree attains a breastheight diameter of at least 12 inches. The larger cottonwood trees contain a very large proportion of merchantable lumber—about 80 per cent of the total volume. The wood is used for coarse lumber. Its toughness fits it for bridge planking and it is also used to some extent for pulp. In the prairie States, cottonwood brings about $10 per thousand board feet on the stump, and $2 per cord for fuel. A large part of the volume of cottonwood could be utilized for posts which can be made very serviceable by preservative treatment.[1]

In the following estimates logs are used for lumber down to a diameter, outside bark, of about 8 inches, and allowance is made for very large or loose knots. Fuel has been estimated with the bark on at the rate of 90 cubic feet per cord, taking all limbs and unmerchantable parts down to a middle diameter limit of 2 inches.

All of the cottonwood stands for which figures are given have been produced on Class A situations; in Kansas, on the sandy bottom lands of the Arkansas River; in Nebraska, on the Platte and Loup River bottoms, and in Minnesota, on low, continually moist, and fairly rich land. The height of trees in Minnesota is strikingly greater than in Kansas or Nebraska for groves of the same age.

The acreage chargeable to cottonwood rows has been computed on the basis of the damage to corn crops. Table 3 shows that with north-south rows this amounts to 132.38 per cent of the crop which might be grown on a strip as wide as the height of the trees. Supplying this factor 1.3238 for CF in equation (1), we have, for a cottonwood row 1 mile long—

$$A = \frac{1.3238 \times H \times \frac{3}{5} \times 5280}{43560}$$

where H is the height of the trees in feet. In a case like No. 3 (Table 17), consisting of 5 rows, 3 feet apart (total thickness 12 feet), we get, by equation (3)—

$$A = \frac{(12 + 1.3238 \times H \times \frac{3}{5})\ 5280}{43560}$$

No measurements of crops south of cottonwood have been made. On the basis of the amount of shade on that side it may be estimated that the damage to crops will not exceed 20 per cent. Adding this to the measured damage on the north side, 63.9 per cent, gives for the east-west row $CF = 0.839$ and the equation for acreage,

$$A = \frac{0.839 \times H \times \frac{3}{5} \times 5280}{43560}$$

[1] Forest Service Circular 117, "The Preservative Treatment of Fence Posts."

TABLE 17.—*Cottonwood estimates—lumber and fuel.*

Serial No.	Type of windbreak.	Orientation.	Age.	Height.	Area sampled.	Volume cordwood.	Volume lumber.	Volume lumber.	Value per mile.	Value per acre (average area since starting).	Value per acre-year without interest.	Annual value per acre, 4 per cent interest.
	No. of rows.		*Yrs.*	*Feet.*	*Acres.*	*Cu. ft.*	*Ft. b. m.*	*P. ct.*				
1	1	North-south	29	70	1.684	3,539	7,236	29.0	$604.00	$89.62	$4.48	$3.011
2	4	....do.....	26	65	.627	1,175	5,231	47.1	706.00	140.90	5.42	3.18
3	5	....do.....	30	65	.146	241	1,222	51.4	931.00	120.70	4.02	[1] 2.15
4	2	....do.....	35	83	.0942	154	1,426	64.9	933.00	187.50	5.36	2.546
5	1	....do.....	40	100	.1822	219	3,677	77.1	2,193.00	228.25	5.71	2.403
6	1	....do.....	40	100	.519	312	6,441	79.8	3,270.00	238.80	5.97	[2] 2.513
7	3	East-west...	24	43	1.917	4,238	(3)	.....	189.20	49.35	2.64	[4] 1.263
8	3	....do.....	31	85	.219	461	1,475	39.0	799.00	113.90	3.67	1.922
9	1	....do.....	38	88	.1016	350	2,314	56.9	1,634.00	304.50	8.01	3.55
10	1	....do.....	40	97	.506	771	6,808	61.33	2,206.00	282.60	7.06	2.97
11	Grove.	.....	10	50	.0492	143	None.	.....	.....	64.70	6.47	5.39
12	Grove.	.....	14	71	.662	1,567	None.	.....	.....	52.62	3.76	[5] 2.88
13	Grove.	.....	16	65	.0536	2,114	None.	.....	.....	87.30	5.46	4.00
14	Grove.	.....	20	60	.403	1,008	None.	.....	.....	55.60	2.78	[6] 1.866
15	Grove.	.....	20	70	.805	2,217	4,074	26.7	.....	113.10	5.66	3.802
16	Grove.	.....	21	60	1.000	3,409	.....	.....	.....	75.75	3.61	[7] 2.27
17	Grove.	.....	25	70	.1205	221	1,277	53.6	.....	147.40	5.90	3.54
18	Grove.	.....	28-34	69	.100	351	1,431	44.9	.....	221.10	7.90	[8] 4.42
19	Grove.	.....	34	80	.200	426	2,880	57.5	.....	191.00	5.62	[9] 2.73
20	Grove.	.....	40	85	.327	189	2,919	73.7	.....	303.00	7.58	[10] 3.19

[1] Ten cubic feet of maple cordwood mixed with cottonwood.
[2] Four rows ash on east, which are partially suppressed; value added to that of cottonwood.
[3] Not estimated.
[4] Some fuel removed in past.
[5] Carolina poplar.
[6] Soil moist, but rather light, sandy.
[7] Contains considerable saw stuff which was not estimated.
[8] Burned out at age of 5–6 years—hence has value of coppice.
[9] Some fuel removed from time to time.
[10] Three thousand feet of lumber per acre removed two years prior to estimate—value calculated to date.

The points in Table 17 which bear upon the method of planting for windbreak purposes are—

(1) The value per mile of the north-south row is strikingly greater than that of the east-west row of the same age.

(2) With these figures reduced to acre values, the discrepancy practically disappears, except in the youngest windbreaks. In the latter it seems that the north-south row gains in diameter and in value more rapidly than the east-west row.

(3) The percentage of volume merchantable for lumber is about the same at all ages in the north-south row and in the grove, but at the same ages is much lower in the east-west row.

(4) The high annual value of groves is maintained by their rapid increase in quality after the trees attain log size and there is every indication that the maximum would not be reached for several years after the age of 40. The relative value of rows and groves in this respect is not clearly shown by any of these figures because from the start the grove has been charged with the same area, which is not increasing in size, while the row was at first charged with only a narrow strip. Hence a sustained mean annual value per acre indicates a much greater current value in the old grove than in the row.

(5) The revenue has been slightly increased, and the efficiency of the windbreak very greatly increased by underplanting the grove with ash about six years after the first planting (No. 20).

GREEN ASH.

Green ash is one of the slowest growing trees planted in the Middle West, but because of the high value of the wood, and of the ability of the trees to resist drought, it has been considerably used in windbreaks, especially in Nebraska. The tree grows better on upland situations than any others except osage orange and honey locust, and has in some instances survived drought which was fatal to almost every other kind of tree. The wood of green ash compares favorably in strength with that of the other ashes of the eastern hardwood forests, but the plantations in the West have not yet begun to yield saw timber. Green ash is one of the most useful trees of the western woodlot, for farm repairs, but has so far been principally used for fence posts. Quartered posts are strong and durable if well seasoned, but they are less durable than osage orange, black locust, mulberry, or catalpa.

Green ash loses its lower branches at an early age, and the foliage is not dense enough to form a barrier to the wind except as the tree is planted in wide belts or groves. As it is essentially a forest tree, it will be found to yield the best returns when planted rather closely in groves. It is a good auxiliary to cottonwood, either for underplanting or side planting, since its slow growth leaves it much below the cottonwood and permits it to fill up the openings left by the death of the cottonwood limbs. Ash grows moderately well in the partial light under cottonwood, but its roots are not so deep as might be desired for a tree in this position.

Table 18 gives the value of ash posts. The measurements have all been made in the interior of belts and groves.

TABLE 18.—*Green ash estimates—posts.*

Serial No.	Quality of situation.	Age.	Height.	Value of posts per acre.			Firsts and seconds.	Spacing—number of trees per acre.
				Total.	Per annum.			
					Without interest.	4 per cent interest.		
		Years.	*Feet.*				*Per cent.*	
1	A	19	28	$147.10	$7.74	$5.32	25.5	1,000
2	B	23	30	272.50	11.85	7.44	39.3	1,274
3	B	23	22	137.20	5.97	3.75	41.6	908
4	A	25	49	270.90	10.84	6.51	49.7	680
5	B	35	25	135.00	3.86	1.83	42.7	436
6	A	40	53	240.45	6.01	2.53	67.5	500
7	A	40	45	250.60	6.26	2.64	70.5	535

The following points are brought out by Table 18: (1) The highest annual returns from posts will be obtained from green ash at the end of about 25 years, after which the growth will not keep pace with the increasing interest. (2) Ash posts of the best quality can be obtained only at a much greater age, and this indicates that a longer rotation is

FIG. 1.—A THRIFTY COTTONWOOD GROVE WITH POSSIBILITIES FOR HIGH FUTURE VALUE. AGE, 10 YEARS.

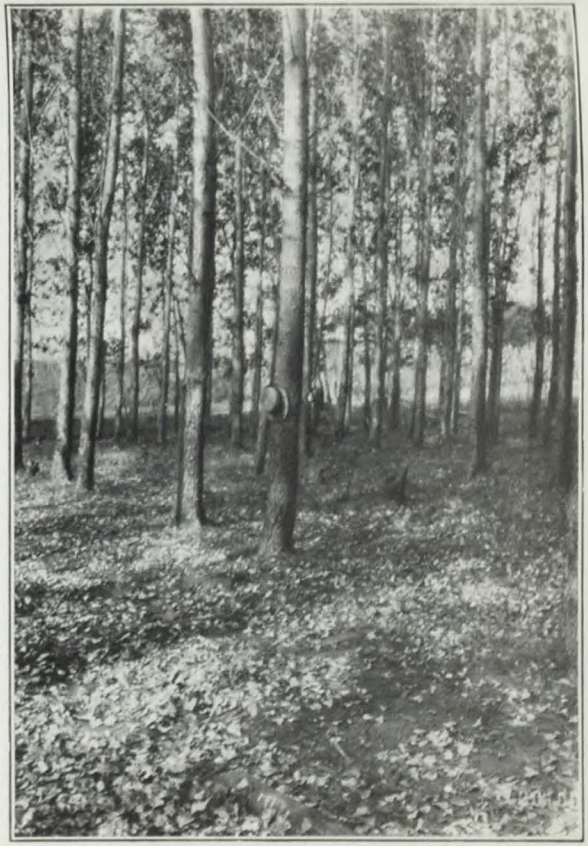

FIG. 2.—CONDITIONS WITHIN THE GROVE FAVOR THE PRODUCTION OF STRAIGHT, SOUND LOGS.

desirable. (3) The best posts are obtained with the closest spacing in groves. Without close spacing the trees are crooked, branchy, and knotty. (4) Dry situations greatly retard the growth of ash, and since its rotation is long on the best situations, it should not be planted on the poorer ones unless needed for protection.

SILVER MAPLE.

The silver or soft maple is a native of the river banks and well-watered lands of the Middle West. It is a moderately rapid grower, but its wood is not durable, and for posts is no more valuable than cottonwood and willow. The timber is principally useful for fuel.

Soft maple is a fairly vigorous rooter and succeeds on moderately dry uplands. The tree supports a rather large and dense crown, which makes it especially valuable for protective purposes. The lower branches persist, with their foliage, as long as they can obtain any light, so that even a single row of soft maple makes a fairly dense windbreak. The tree has been chiefly planted in belts and groves. The area charged to maple on the edges of belts and groves is calculated on the basis of the damage to corn. This was found to be 61.43 per cent for the north side and 62.90 per cent for the south side.

The estimates of silver maple given in Table 19 include the entire volume usable for fuel.

TABLE 19.—*Silver maple estimates—cordwood.*

Serial No.	Orientation and class.	Quality of situation.	Age.	Height.	Volume per acre.		Value of cordwood per acre.		
					Cubic feet.	Cords.	Total.	Per annum.	
								Without interest.	4 per cent interest.
			Years.	*Feet.*					
1	East-west belt	A	19	33	1,333	14.81	$29.62	$1.56	$1.07
2	do	A	24	45	2,708	30.09	60.18	2.57	1.54
3	Grove	A	25	58	2,605	28.94	57.88	2.32	1.39
4	East-west belt	A	26	44	2,735	30.39	60.78	2.34	1.37
5	do	A	26	44	2,497	27.74	55.48	2.13	1.25
6	Grove	B	34	45	2,275	25.28	50.56	1.48	.72

WILLOW.

Willow is not a valuable tree, but on good, moist soil it grows very rapidly at the start, and in a few years will furnish an immense amount of material, of which most has some usefulness in the form of posts and all may be used for fuel. Willow posts of the commonly planted species are not durable, but are somewhat more valuable than cottonwood posts. "Diamond willow" (*Salix cordata mackenziana* Hook), on the other hand, a native along the banks of some of the streams in Nebraska, is very durable, and surpasses almost any of the native species for posts and fuel. The willow commonly planted in northern

Nebraska, Iowa, and Minnesota is the white willow (*Salix alba* Linn) of Europe. This is very short-lived and attains its greatest annual value at the end of 10 years. Because of its early rapid growth it must be considered a useful tree. It makes severe drains on soil moisture, and as its roots are almost wholly laterals and close to the surface, it does considerable damage along the edges of fields. On this account farmers in Iowa and Minnesota have to a large extent removed the rows of willows which formerly surrounded their fields.

In Tables 20 and 21 the area charged to single rows of willow has been calculated on the basis of the damage to a crop of oats in the season of 1908. The damage was apparent out to about twice the tree height, and amounted on either side of the north-south windbreak to the complete loss of grain in a strip almost exactly as wide as the height of the trees.

TABLE 20.—*White willow estimates—posts.*

(All on quality A situations.)

Serial No.	Orientation and class.	Age.	Value per mile.	Height.	Area charged.	Value per acre.			Posts—firsts and seconds.
						Total.	Per annum.		
							Without interest.	4 per cent interest.	
		Years.		*Feet.*	*Acres.*				*Per cent.*
1	North-south row.	14	$1,401.79	30	4.85	$289.15	20.65	15.81	63.5
2	do	15	1,139.38	33	4.835	235.70	15.71	11.77	55.1
3	do	17	1,119.38	38	5.531	202.40	11.91	8.54	66.1
4	do	18	909.21	38	5.531	164.45	9.14	6.67	58.8
5	do	20	707.95	31	4.512	156.95	7.85	5.27	56.3
6	do	23	1,314.92	42	6.112	215.15	9.35	5.88	57.8
7	do	25	1,060.79	42	6.112	173.55	6.94	4.17	69.0
8	East-west belt [1]	14	2,637.00	42	9.51	277.40	19.81	15.17	61.4
9	do. [2]	14	3,109.00	40	11.27	275.80	19.70	15.08	56.8
10	Grove	18	.....	36	.....	317.00	17.61	12.36	58.6
11	do	18	.....	32	.....	316.90	17.61	12.36	52.1
12	do	25	.....	48	.....	508.00	20.32	12.20	64.3

[1] Three rows, 14 feet apart. [2] Four rows, 15 feet apart.

TABLE 21.—*White willow estimates—fuel.*

Serial No. (refer to last table).	Orientation and class.	Age.	Height.	Volume per acre.		Value per acre.		
						Total.	Per annum.	
							Without interest.	4 per cent interest.
		Years.	*Feet.*	*Cu. ft.*	*Cords.*			
2	North-south row	15	35	2,142	23.8	$47.60	$3.17	$2.35
3	do	17	38	2,802	31.13	62.26	3.66	2.63
4	do	18	38	2,276	25.3	50.60	2.81	1.47
7	do	25	42	2,484	27.6	55.20	2.21	1.32
9	East-west belt	14	40	1,856	20.62	41.24	2.94	2.25
10	Grove	18	36	3,212	35.7	71.40	3.97	2.78
11	do	18	32	2,384	26.5	53.00	2.94	2.07
12	do	25	48	2,586	28.73	57.46	2.30	1.38
13	do	31	58	1,930	21.44	42.88	1.38	.72

Tables 20 and 21 indicate the following points which are of interest to windbreak planters:

(1) The value of willow posts is five or six times as great as that of the same material used for fuel at the price of $2 per cord.

(2) The annual acre value of young willow which may be used for posts is very high, by reason of the vigorous root growth and stem development in early age.

(3) The short-lived character of white willow and the importance of the factor of interest makes the growing of willow to old age unprofitable. In post production, the value of single rows seems to decrease steadily after the fourteenth year.

(4) The financial rotation of trees in the interior of groves and belts is not reached so soon, because their claims on land remain stationary and because the development is not so rapid when the trees are crowded on all sides.

HONEY LOCUST.

Honey locust grows with fair rapidity. Its wood is fairly hard and strong and the heartwood is durable in contact with the soil and compares favorably with green ash, but is not equal to mulberry, catalpa, black locust, or osage orange.

The tree should be handled on a short rotation. It grows equally well in closely planted groves and in hedge rows, but to obtain efficient protection groves or wide belts will be found necessary. Mixture with a more tolerant deep-rooted species is desirable, since honey locust appears to lack any special ability for extending its roots in search of water. The tree does well on moderately dry uplands where the soil is heavy.

Table 22 gives the results of examinations of groves and rows of this species. The cases have been grouped according to the quality of the situation in which they were found. The area charged to single rows of this species was calculated on the basis of the damage to alfalfa west of a honey-locust hedge, and the damage on other sides was considered proportional to the amount of light cut off on these sides. The damage to alfalfa west amounted to 56.25 per cent, while the value of the shade on that side was 42.53 per cent. The value of the entire shade for a north-south row is 98.91 per cent, and the probable total shading damage $\frac{56.25 \times 98.91}{42.53} = 130.8$ per cent. The value of the shade of an east-west row was found to be 125.89 per cent. The probable damage to crops is therefore 166.5 per cent.

TABLE 22.—*Honey locust estimates—posts.*

Serial No.	Quality of situation.	Orientation and class.	Age.	Value per mile.	Height.	Acreage charged.	Value per acre.			Posts—firsts and seconds.	Remarks.
							Total.	Per year.			
								Without interest.	With interest, 4 per cent.		
			Yrs.		*Feet.*					*P. ct.*	
1	A	North-south row	10	$587.49	22	2.093	$280.90	$28.05	$23.35	35.8	Coppice.
2	A	....do.....	22	349.44	30	2.854	122.50	5.57	3.57	13.5	Underestimated.
3	A	....do.....	34	853.76	35	3.330	256.45	7.55	3.67	45.9	Do.
4	A	East-west row...	34	608.00	35	4.235	143.62	4.23	2.06	37.1	Do.
5	A	....do.....	25	324.80	35	4.235	76.70	3.07	1.84	20.5	Do.
6	A	....do.....	40	1,057.92	32	3.872	277.30	6.84	2.87	49.3	Good; no cultivation.
7	B	North-south row	11	915.89	33	3.142	291.60	26.50	21.60	53.7	Coppice.
8	B	....do.....	31	926.37	40	3.807	243.35	7.85	4.10	51.9	Normal.
9	B	East-west row...	28	469.83	25	3.026	155.30	5.55	3.11	50.6	Do.
10	B	....do.....	20	373.44	18	2.178	171.45	8.58	5.76	21.2	Good; coppiced young.
11	B	....do.....	24	364.89	25	3.026	120.60	5.03	3.09	20.7	Good row.
12	B	....do.....	30	197.76	26	3.146	62.88	2.10	1.12	43.1	Underestimated.
13	B	....do.....	30	182.40	27	3.267	55.83	1.86	1.00	46.3	Do.
14	A	Grove.....	29	.....	.....	.....	287.40	9.91	5.42	45.3	Bottom land.
15	B	....do.....	26	.....	25	.....	167.10	6.43	3.77	50.3	Upland.
16	C	....do.....	23	.....	14	.....	102.52	4.46	2.80	34.2	Do.
17	D	East-west belt .	28	.....	15	.....	98.90	3.53	1.98	28.9	Upland; very dry.

Examination of Table 22 shows the following points which are of interest to the windbreak planter:

(1) The value of rows of both orientations and of groves is about the same when calculated on an acre basis and amounts on first-class situations to $3.50 to $5 per acre per annum. On very dry situations it will not exceed $2 per acre per annum.

(2) The quality of posts produced increases with the age. It is not greater in the case of groves than in rows.

(3) The annual acre value of coppiced honey locust is very high. But since this remarkable growth is made upon the roots of old trees, whose sapping effect is apparent over a wide area, it is necessary to calculate the acre value on the basis of the area sapped. It is impossible to do this except in a most general way. From the data at hand it is believed that the annual acre values of Nos. 1 and 7 should not be placed higher than $8 and $7, respectively.

OSAGE ORANGE.

The osage orange or "hedge" has been very extensively planted throughout the southern portion of the range of this study. It is primarily a tree for hedges and when so used makes a highly efficient windbreak. The main objection to osage orange, that it tends to extend its roots very widely, is well grounded. It is partly because of this remarkable root vigor, but more because of the very high value of the post material yielded by osage orange that the returns are so large. The wood is more durable in contact with the soil than that of any other tree cultivated in the West. The presence of

thorns on the trees makes it very difficult to cut them, but adds greatly to the value of the hedges.

In Table 23 the hedges are grouped first according to orientation and then according to quality of situation and age. Under "Remarks" attention is called to the influences that bear upon the final value and to the comparisons which most forcibly demonstrate that value.

The factor for computing the acreage devoted to an osage orange hedge is obtained from Table 3. The sum of the areas used on the north and south sides is 1.2691 and on the east and west sides 1.7402 times the height of the trees.

TABLE 23.—*Osage orange estimates—posts.*

Serial No.	Quality of situation.	Orientation of hedge.	Age.	Value per mile.	Height.	Acreage per mile.	Value per acre.			Proportion of first and second grade posts.	Remarks.
							Total.	Per year.			
								Without interest.	4 per cent interest.		
			Yrs.		*Ft.*					*P. ct.*	
1	A	North-south...	25	$1,011.84	26	3.290	$307.50	$12.30	$7.39	56.3	Cultivated both sides.
2	A	.....do.....	31	809.76	22	2.783	312.70	10.09	5.27	31.4	No cultivation.
3	B	.....do.....	20	1,130.88	24	3.037	372.35	18.62	12.51	39.6	Very good soil; cultivated both sides; compare No. 11.
4	B	.....do.....	21	445.44	24	3.037	146.70	6.99	4.59	20.9	Coppice; cultivated one side.
5	B	.....do.....	22	960.00	25	3.163	303.60	13.80	8.86	45.7	Do.
6	B	.....do.....	23	1,153.02	21	2.658	433.80	18.86	11.85	49.6	Very good soil; cultivation one side; compare No. 3.
7	B	.....do.....	23	836.22	20	2.530	330.60	14.37	9.02	36.3	Pasture one side.
8	B	.....do.....	25	579.84	23	2.910	199.30	7.97	4.79	18.8	Coppice.
9	B	.....do.....	30	698.88	25	3.163	221.00	7.37	3.94	33.3	Cultivated one side.
10	B	.....do.....	31	1,284.48	28	3.542	362.65	11.70	6.11	50.5	Cultivated both sides at present.
11	B	East-west.....	20	785.64	25	2.308	340.50	17.02	11.43	47.4	Cultivated both sides; compare No. 3, north-south.
12	B	.....do.....	30	777.60	20	1.846	421.50	14.05	7.52	25.6	Cultivated both sides; compare No. 5, coppice.
13	B	.....do.....	31	828.18	30	2.769	299.25	9.65	5.04	49.6	Lately cultivated one side; compare No. 10, north-south.
14	C	.....do.....	21	121.50	13	1.200	101.25	4.82	3.17	11.1	No cultivation; compare No. 15.
15	C	.....do.....	21	292.26	16	1.477	197.90	9.42	6.19	38.3	Cultivated one side; compare No. 14.
16	D	.....do.....	36	126.66	15	1.384	91.50	2.54	1.18	14.9	Cultivated both sides at present.

The following points bear especially upon the windbreak problem:

(1) The mile value of north-south hedges is considerably greater than east-west hedges. Even when reduced to acre values, the area charged having been calculated from the loss to corn crops from shading, the north-south windbreaks are still found to have a slightly higher value. This is to be accounted for by slight error in arriving at the reducing factors for the two orientations.

(2) The post value of osage is higher than that of honey locust and other species which grow on situations of the same quality. This is

partly due to the wider root extent of osage, and, in dry years, when sapping was pronounced, it would be necessary to charge this species with use of a greater area than that demanded by the shorter-rooted trees.

(3) The effect of cultivation, especially in the poorer situations, is as marked in *increasing* the growth and post value of hedges as it was found to be in *reducing* the root extent.

(4) The cutting back or coppicing of osage orange does not bring especially rapid or heavy returns, although sprouts are produced in abundance, and they grow thriftily for several years. Examination of the last column of figures in the table shows that these sprouts do not produce first-class posts. More heavy thinning should be resorted to. Measurements have shown that coppice osage has the same power for sapping as did the larger trees from which it originated. This energy can be made to produce merchantable stuff if the proper methods are used.

RUSSIAN MULBERRY.

The Russian mulberry has been planted extensively in Nebraska and Kansas, and on account of its very vigorous and rapid growth yields a good revenue from posts at an early age. Mulberry posts are very durable, especially when they contain a large proportion of heartwood, and they compare favorably with catalpa in all sizes. They are more lasting than green ash or honey locust, but inferior to black locust and osage orange. Russian mulberry is not hardy in the North, and freezes back each winter so severely as greatly to reduce its value. Even in western Kansas it is likely to be winter-killed where moisture is not abundant. In good situations the damage to the smaller branches in winter does not prevent its yielding profitably. Very valuable mulberry has been found on rather dry situations, where sheltered by other trees. The tree is fairly drought-resistant, having very extensive roots, and it is a very vigorous sprouter. It is considered a severe sapper when planted next to field crops, but as a shelter for orchards it is not likely to be harmful from this attribute. Besides forming a dense and almost impenetrable windbreak, mulberry has the additional value, when planted about orchards, of furnishing an inferior fruit, which is eaten by birds in preference to the more valuable orchard products. It has its greatest value in this respect in protecting cherry orchards.

The area charged to mulberry rows has been calculated on the basis of its branching extent as compared to osage orange, since it is probable that the amount of damage in the shaded zone will be approximately the same for both.

Table 24 gives the results of the estimates of posts in seven mulberry hedges, all but the last two being single rows. No. 7 represents a row on the south side of a belt of ash, maple, and willow, and No. 6 is two rows 5 feet apart.

TABLE 24.—*Russian mulberry—estimates of posts.*

Serial No.	Quality of situation.	Orientation and class.	Age.	Value per mile.	Height.	Acreage charged.	Value per acre.			Proportion of first and second grade posts.
							Total.	Per year.		
								Without interest.	4 per cent interest.	
			Yrs.		*Feet.*					*Per ct.*
1	A	North-south row	11	$1,028.67	23	2.885	$356.70	$32.42	26.52	42.9
2	A	do	12	727.65	25	3.135	232.00	19.33	15.45	34.6
3	A	East-west row	8	369.49	22	2.168	170.50	21.33	18.50	31.3
4	A	do	10	696.99	18	1.773	393.05	39.30	32.75	29.1
5	A	do	12	467.51	25	2.465	189.70	15.81	12.63	34.2
6	A	East-west, 2 rows	12	1,039.01	24	2.972	349.60	29.13	19.91	28.6
7	B	East-west, row in grove	22	475.20	28	1.637	290.30	13.20	8.48	33.8

The points especially worthy of note are:

(1) The acre value of young mulberry is very high and in nearly every case is greater than the highest value of white willow on A-class situations. This is due to the tremendous root vigor of mulberry. If it is planted adjacent to field crops, a much larger area would be chargeable to the trees in dry years than has been used in these calculations.

(2) Even on moderately dry situations mulberry produces a good revenue from posts when protected by other trees. An outer row, in No. 7, was exposed to south winds and was much poorer than the inside row; in fact, many of the trees had died.

(3) In spite of the low value assigned to the smaller posts of mulberry, which are almost wholly sapwood, the immense number of shoots from the same root stock makes these an important item. The most valuable hedges are those with a large proportion of third-class posts.

(4) The wide root system of mulberry, supporting numerous stems and a dense mass of foliage, gives it unusual value for protection purposes.

CATALPA.

The hardy catalpa, although a valuable tree for post and pole production in the Middle West, can not be considered a good tree for windbreak planting, unless the probable revenue from a grove may be made to compare favorably with the income from field crops on the same ground. The catalpa is essentially a forest tree. It does not succeed in unsheltered situations because of its slight power of resisting the influence of dry winds. Hence, unlike several of the

other species which produce only posts, it is not adapted to single-row planting. On the other hand, the height attained by catalpa is not sufficient to make the use of wide belts or groves justifiable. Unless planted in wide belts, catalpa can not form an efficient windbreak, because it is an intolerant tree and its lower branches are lost at an early age, leaving clean boles, which offer little resistance to the wind.

A single grove of catalpa, growing on land of the finest quality in Nebraska, at the age of 18 years had a value in posts of $289.30 per acre, or an annual value with 4 per cent interest of $11.28 per acre. Without interest, the value of the grove is $16.17 per acre each year, exclusive of the cost of planting and tending. The posts in this grove numbered about 2,820 per acre, of which 42 per cent may be classed as firsts and seconds. The height of the grove was about 25 feet. This is somewhat less tall than groves on first-class land, but is fairly characteristic of the tree.

WHITE PINE.

Of the conifers which may be planted on good soils in Iowa and Minnesota, and perhaps also in the best sheltered situations in Nebraska and eastern Kansas, none promises so much in the way of vigorous growth and profitable yield as white pine. The thrift and quality of the tree, the usefulness of its lumber, and its protective and esthetic values will all lead to a greater utilization of white pine throughout the Eastern and Lake States, and as far west as the tree may be grown without danger of winterkilling. There is every reason to believe that if planted on moist, fertile soil, and protected from the direct effects of drying winter winds, this tree will succeed to middle western Nebraska and central Kansas. Young trees of this species are doing well on the Platte River bottomland at Grand Island, Nebr., and trees about 30 years old are growing at Hutchinson, Kans., in the valley of the Arkansas River.

The extension of the box-board industry by means of small portable sawmills will make the harvesting of white pine at an early age both possible and profitable. Forest-grown white pine can not be cut profitably for ordinary heavy lumber before it is about 60 years old. But it has been very clearly shown that white pine grown in narrow belts or even single rows in northeastern Iowa produces good straight boles, fairly free of branches, and attains log size much sooner than trees in groves. In Fayette County, Iowa, an orchard owner planted belts of about three rows of white pine at intervals of 40 rods, running east and west. At the age of 40 years many of the trees contain logs 16 to 20 inches in diameter, from which a large amount of construction timber has been sawed. The trees of the middle row in these belts are much smaller than those on the outside, but their

stems are clearer. According to the owner, the white pine causes very little damage to crops growing adjacent to it.

A small grove of white pine in the same county, 37 years old, now contains 1,030 trees to the acre, with a total volume of 7,785 cubic feet, or an annual increment of 210 cubic feet. The trees are growing on first-class upland loam soil, and are very thrifty and well formed. The present average breast-high diameter is 7 inches.

It is impossible to estimate the present value of this grove, because there are no industries near that might utilize to the best advantage the products of the trees. It is fairly safe to say, however, that 70 per cent of the volume of the grove might be utilized for box boards, cutting to a diameter of 4 inches. This material may be valued at $6 per cord, on the stump, while the remainder will be worth $2 for fuel. On this basis the present value of the grove is $415.20 per acre, which represents an annual income, with interest at 4 per cent, of $5.08 per acre.

SCOTCH PINE.

The Scotch pine, a native of Europe, and the most important conifer in the lumber trade of Europe, has been considerably planted throughout the Middle West, where it grows rapidly and is extremely useful for ornamental planting. Although it produces well in Europe, examples of successful plantations in this country are extremely rare, and the tree has gained a bad name because of its rather branchy habit and poor development.

In view of its hardiness and high protection value, it is fortunate that the possibilities of Scotch pine for commercial purposes have been demonstrated in at least one instance. There is a good grove of Scotch pine on rich dark clay loam in a poorly drained situation in Watonwan County, Minn. The trees were from 35 to 38 feet high at the age of 19 years from seed. The stand contained 1,775 trees per acre, having been planted with about 4,000 trees to the acre. The average diameter breast high was 4.73 inches. The greatest height growth had been made between the ages of 7 and 14 years, when it averaged 29.4 inches per year.

The volume of the grove was 4,122 cubic feet per acre, or an average annual increment of 217 cubic feet per acre. While the trees at the time of measurement were too small to be of use for anything but fuel, it may readily be seen that the growth of this grove is very promising. In a few years it may be expected to yield a heavy cut of material suitable for box boards. Calculating the fuel value at the present time at $2 per cord, the return is $91.60 per acre, or an annual income, with interest at 4 per cent, of $3.31 per acre.

There can be no doubt that when planted closely on moist situations Scotch pine will grow rapidly and in good form, and may readily compete with any of the native conifers in volume increment.

PART IV.

SUMMARY.

CALCULATION OF THE SIZE OF EFFICIENT WINDBREAKS.

The protective value of an osage-orange hedge in the season of 1908 was equal to the yield of a strip twice as wide as the height of the trees. The protection afforded by the most efficient grove windbreaks amounted to the yield of a strip three times as wide as the height of the trees. This means that the farmer in the Middle West can afford to maintain a windbreak running through the farm from east to west, and having a width of 240 feet in the case of mature cottonwoods 80 feet high. On a farm of 160 acres this would give approximately 15 acres of timber, or about 10 per cent of the area. There should be at least two such strips, however, to protect the entire farm from both north and south winds. This is the recommendation made by European agricultural economists, that 20 per cent of the farm should be in forests. Such windbreaks as these, by protection alone, will pay a rental on the ground which they occupy equal to that from grain crops.

In addition to the protection it has been shown that windbreaks of nearly every species planted in the Middle West have a high timber value at maturity.

SIZE OF EFFICIENT WINDBREAKS DETERMINED BY THEIR VALUES.

GROVES AND SHELTER BELTS.

The figures which represent the protective value of windbreaks apply only after the windbreaks, or more properly the trees within them, have become mature, and do not take into account the fact that the protective value of a belt of young trees is much less in proportion to its width than the protection afforded when the trees have attained their full height. In most cases it would not be practicable to gradually increase the width of the windbreak as the trees become taller, and it is, generally speaking, more profitable from the lumberman's standpoint to make a clean cutting when the timber is harvested; it is, therefore, necessary to calculate the total protective value of the windbreak from the time of planting to maturity, and to balance this against the total value of crops which might have been grown on the land occupied by the trees during the same period.

Roughly, the average protection given by the belt of trees is one-half as great as that given at maturity, since it increases directly

with the height of the trees. But in most cases the height growth of the trees is much more rapid in the first half of the period than in the second half. This is especially true of cottonwood. Table 25 gives the height at different ages and under varying conditions.

TABLE 25.—*Height growth of cottonwood.*

Age.	Kind of windbreak and quality of situation.		
	Grove.		Row or narrow belt.
	Class A.	Class B.	Class A.
Years.	*Feet.*	*Feet.*	*Feet.*
5	20.0	10.8	15.0
10	39.0	19.5	25.6
15	52.4	27.5	35.7
20	62.0	35.5	45.7
25	69.3	42.7	55.8
30	75.5	49.4	65.9
35	81.1	55.2	76.0
40	86.2	60.5	86.1

This shows that the height growth in groves is very rapid at the outset, but that the rate of growth decreases after the trees begin to crowd each other for root space. In rows and narrow belts there is less incentive to rapid height growth at the start, because the trees may develop more fully their side branches. But the rate of growth is maintained very uniformly up to the fortieth year, at which time the height of the trees in a row will be almost the same as in a grove. Beyond this age, which represents maturity for cottonwood, it is probable that the rate of growth falls off rapidly in both cases.

If the benefit is calculated for each year from the time of planting, on the basis of the height of the trees, and if these annual incomes are carried with compound interest to the time of maturity of the timber at the end of a 40-year rotation, the protective value of a good cottonwood windbreak a mile long amounts to $35,585.50. Against this must be balanced the value of the grain crops which might have been grown each year. Using $22.50 per acre, or 45 bushels of corn at 50 cents, the gross grain value taken for calculating benefit, these successive crops at the end of 40 years, with interest to the end of the period, may be valued at $2,138. To this must be added the initial cost of planting an acre, $10, with interest, making $48.01. Therefore the total cost of the windbreak has been $2,186.01 per acre, and its protective value has been sufficient to pay the entire cost of 16.28 acres. Even supposing that the windbreak has no timber value, or that it can not be cut without endangering the adjacent crops, then the protective value up to 40 years has paid a full crop rental on all the land occupied by a belt of trees with a width of 134 feet, which is equal to 1.55 times the height of the mature trees.

But on the basis that the timber crop is to be cut at 40 years, and that the value of this, if not burdened with interest, is comparable to the net value of field crops, the annual protective value may be balanced against the accrued interest on the initial cost of planting and on the crop value of the land. Using the same figures and simply deducting the crop value ($40 \times \$22.50$) and initial cost, \$10, it is found that the interest amounts to \$1,276.01. With only this interest to pay, the belt may profitably contain 27.88 acres, and may be 230 feet wide, or 2.67 times the height of the trees.

Whether the high efficiency of the cottonwood windbreak, with a width of only 150 feet, can be maintained when the trees become very old, depends on the quality of the ground on which it is growing, and upon the feasibility of introducing smaller trees which will form an understory and fill up the gaps left by the loss of the lower branches. On poor ground the aggregate protective value up to 40 years is less than on good soil, and it is therefore obviously unprofitable to plant so large an area. With a decreased width and decreased density of stand upon the poorer situations, it becomes necessary to substitute for cottonwood some species of more dense foliage, or one which by reason of greater root vigor and tolerance will form a more compact windbreak. Green ash, osage orange, and several of the drought-resistant conifers, such as Austrian pine, red cedar, and jack pine may be recommended. Mixtures of hardwoods and conifers are desirable wherever winter protection is needed. (See diagram 33.)

In order to make profitable the use of wide windbreaks which have the quality of groves, there must be selected for the main body of the shelter a species which will make rapid height growth at the outset. If necessary, it may be underplanted with a slow-growing, dense-foliaged tree, or the latter may be used along the sides of the grove, and may be planted either at the outset or when the main trees of the grove begin to prune themselves rapidly. Under any circumstances, the total width of the grove (from outside trunk to outside trunk) should not exceed one and one-half or two times the expected height of the trees at maturity.

SINGLE-ROW WINDBREAKS.

In the use of single-row hedges an entirely different and much simpler problem is met. Windbreaks of this class can not, at the outset, be charged with any more space than would be occupied by a fence, and as they increase in height, their beneficial influence will each year increase proportionately. This will at all times far exceed the damage from shading and sapping, so that there will never be any debt to be charged to them. It is only when the hedge is cut back, and entirely robbed of its protective value, that the sapping effect may be seriously felt. With osage orange, this effect may extend over an area three times as wide as the trees were high before

they were cut. If, however, the aggregate benefit up to the time of cutting is calculated, there is in favor of the hedge a considerable surplus which may be used to tide over the few years before the sprouts again become efficient.

Table 26, on which the calculations of benefit are based, shows the height growth on moderately moist to dry situations.

TABLE 26.—*Height growth of osage hedges.*

Age, years.	Situation.			Age, years.	Situation.		
	(A) moderately moist.	(B) slightly moist.	(C) dry.		(A) moderately moist.	(B) slightly moist.	(C) dry.
	Feet.	*Feet.*	*Feet.*		*Feet.*	*Feet.*	*Feet.*
3	8.0	6.5	4.4	21	29.3	22.9	14.5
6	15.0	12.0	7.3	24	30.6	23.7	15.2
9	20.0	15.8	9.6	27	31.7	24.3	15.6
12	23.2	18.3	11.3	30	32.6	24.6	15.9
15	25.7	20.3	12.6	33	33.3	24.8	16.0
18	27.6	21.8	13.7				

Calculating the value of an osage hedge on the basis of an annual net benefit equal to the yield of a strip of ground twice as wide as the height of the trees, there is at the end of 20 years a surplus in favor of the windbreak on B class situation, of $1,980. This is sufficient to pay for the total loss of crop in the area occupied by the old roots, 68 feet wide, for 12 years after the cutting. As a matter of fact, the height growth of osage coppice is so rapid that in a very few years the hedge will again be paying for itself.

The single-row hedge or windbreak must be primarily for the production of posts and small timbers in which freedom from knots is not an essential feature. Protection and high quality timber production can be secured only in the wide windbreak, where forest conditions are obtained, and where the body of the trees, as a whole, forms a barrier to the wind.

The previous discussion has been based on the idea that the most efficient protection is desirable, as for grain crops, for the protection of houses and cattle sheds, and for the purposes of a snow trap. There are situations, however, where a dense windbreak is not desirable, and where the complete stagnation of the air would be injurious. Orchards may sometimes be rendered colder, in the case of a frost on a clear and relatively calm night, and again the danger from fungous diseases is greater in the more humid air behind a windbreak than in the open where the surfaces of leaves and fruit are kept dry by the wind. These fungi are sometimes injurious to grain crops as well as to fruits, and the damage arises during a period of wet weather. The "rust" of wheat and "smut" of oats are of this character. It is reasonable to suppose that the presence of a windbreak favors the growth of these fungi.

Throughout a region, as in all the northern and western parts of the United States, where drying winds are prevalent, where atmospheric moisture is not superabundant, and where the danger from cold storms at the critical time of year is great, it is safe to say that the benefit to be derived from windbreaks of forest trees planted about orchards will at all times far exceed the possible damage from "still" frosts, from fungi, from insects, and from the dwarfing of trees on the edge of the orchard. The storm of 1908 was typical of the storms which occur in some portion of the northern United States nearly every spring. It must be remembered, also, that even when the storm consists of only a dry wind, the tender leaves and flowers may be injuriously cooled by evaporation or blighted by drying out.

WINDBREAKS FOR VARIOUS REGIONS.

Windbreaks may profitably be used in six principal regions of the United States. It is important to know what is the ideal windbreak and what methods are necessary to obtain and maintain it in each of these regions:

(1) The Middle West, including southeastern South Dakota, western Iowa, Nebraska, Kansas, and eastern Colorado.

(2) The Northern Prairies, including eastern Montana, the Dakotas, and southern Minnesota.

(3) The Lake States, including also southeastern Minnesota and northeastern Iowa.

(4) The Eastern States, north of the thirty-ninth parallel.

(5) The Southwestern States, including southwestern Kansas, western Oklahoma and Texas, Arizona and New Mexico.

(6) The fruit-growing regions of the Pacific Coast States.

1. THE MIDDLE WEST.

(*a*) Cottonwood is the tree best suited for windbreaks in the Middle West when these are planted on good, moist situations, on river bottoms, or, in the extreme eastern part of the region, on rolling uplands. The trees should be planted in belts from 125 to 150 feet wide, running east and west, and should not be cut until about 45 years old, when their height will be approximately 90 feet. If practicable, not all of the grove should be planted at the same time, but a narrow strip which will form the center of the final belt should first be set out, and the belt widened as the first planted trees become taller. The range of ages should not be more than 10 years, and the youngest trees should be on the outside, where their effects on crops will be least deleterious.

In a windbreak of cottonwood in which the trees are approximately the same age, underplanting with a tolerant hardwood or

conifer will be necessary to insure the continued efficiency of the belt. Green ash succeeds fairly well when planted a few years after the cottonwood. Red oak should be given a trial. On good ground this species grows rapidly, and will yield post material of about the same value as green ash; or the trees may be retained after the cottonwood is cut, and grown to a larger size.

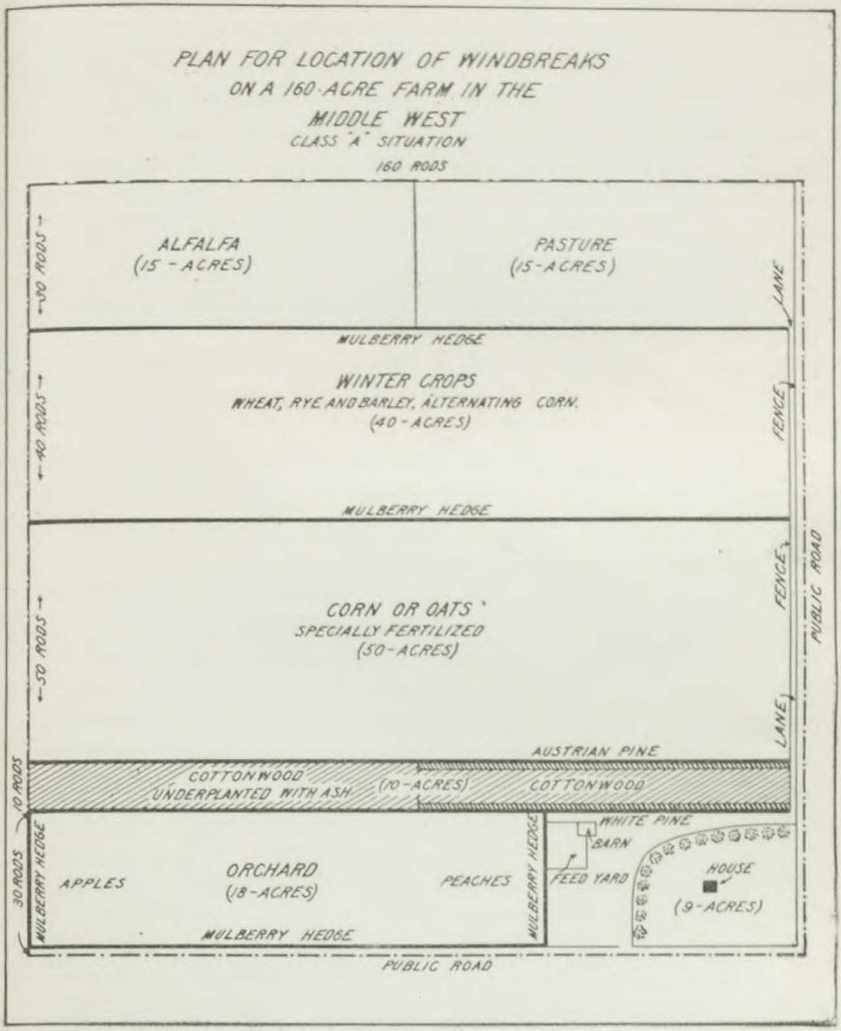

DIAGRAM 35.—Plan for location of windbreaks on a farm in the Middle West.

Of the conifers adapted to use as an understory to cottonwood, the spruces are the most promising. Norway spruce, very successful in the East, will not thrive where moisture is lacking. The same is true of the native eastern spruces. The Black Hills spruce stands the test of summers and winters on the plains of South Dakota.

A modification of underplanting that offers greater possibilities is to leave the cottonwood belt incomplete; that is, not to use the entire area allowed for it and to supplement the cottonwoods, when they begin to thin themselves, with three or four rows of evergreens on either side. Austrian pine should be used on the north side, since it is hardy, dense, and fairly rapid growing, and white pine should do well if planted along the south side where it will not get the full force of drying winter winds. Both of these species will retain their outside branches until the end of the 45-year rotation, and at the same time their shading of adjacent crops will be the least damaging. White cedar or arborvitæ has been successfully grown in Nebraska when not exposed to winter winds. One or two rows of this species would be a valuable auxiliary outside of the white pine on the south side of the belt. Diagram 35 shows the ideal arrangement for a 160-acre farm in the Middle West.

It includes, besides the main belt of cottonwoods, two full length hedges of Russian mulberry and a third protecting the orchard from south winds. It shows the arrangement of windbreaks, which with slight revision will be practicable for any quarter section. The essential features are these:

(1) The house and barn are sheltered from northwest, north, and northeast winds, but not from the summer winds, which are, on the whole, cooling. The width of the grove, 10 rods, is sufficient to make it a snow trap.

(2) The orchard is protected on the north by a dense grove and on the south and west by a mulberry hedge which will thoroughly protect the outer trees and at the same time do little damage by shading or sapping. The fruit of the mulberry will entice the birds from the more valuable orchard products.

(3) The large field to the north of the high cottonwood grove is to be used principally for corn, since the cottonwoods will afford summer protection mainly. If desired, oats or a soiling crop may be used in rotation.

(4) The middle field of 40 acres may well be used for such crops as wheat, rye, and barley, since it is protected from both winter and summer winds.

(5) The north field may be used for hay crops and for pasture. For both of these purposes it will be benefited by the protection from hot south winds.

(6) The use of this combination of species will furnish posts for fencing from the osage, ash timbers for farm repairs, an unlimited supply of cottonwood fuel, and eventually a good revenue from cottonwood lumber. The evergreens used are ornamental, useful for protection of the home, and finally useful for split posts or fuel.

FIG. 1.—A FEW ROWS OF COTTONWOOD, WHEN YOUNG, MAKE A FAIRLY DENSE PROTECTING BELT.

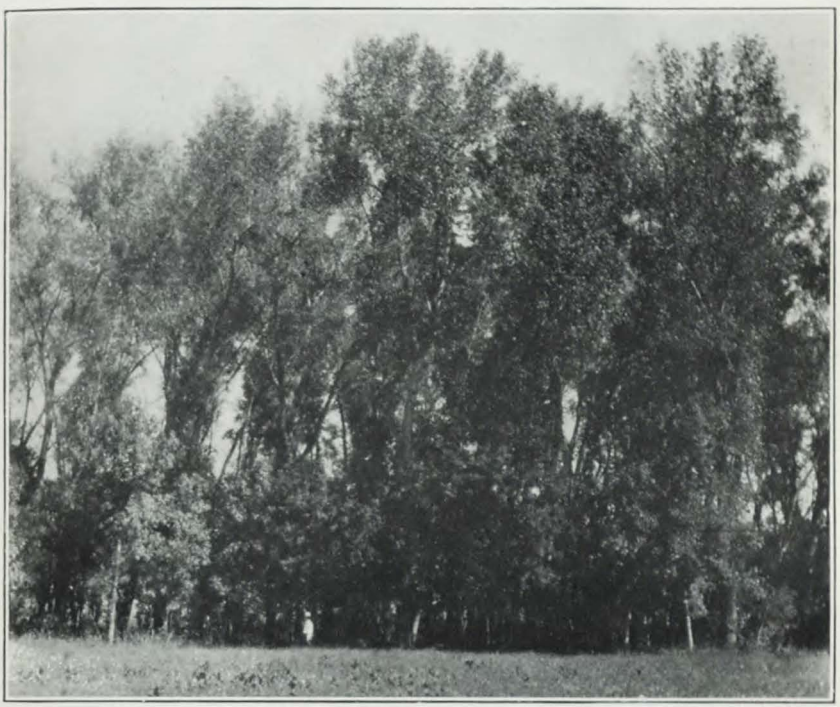

FIG. 2.—WHEN MATURE, COTTONWOOD MUST BE UNDERPLANTED IF THE BELT IS TO RETAIN ITS EFFICIENCY.

GREEN ASH: EVEN A VERY GOOD BELT OF HARDWOODS FORMS A POOR WINTER SHELTER AND SHOULD BE SUPPLEMENTED WITH EVERGREENS.

FIG. 1.—IN CLOSELY PLANTED GROVES WHITE PINE FORMS STRAIGHT, CLEAN BOLES.

FIG. 2.—EVEN IN BELTS OF A FEW ROWS, THE GROWTH OF WHITE PINE IS ERECT AND SYMMETRICAL, BUT THE OUTER TREES WILL RETAIN THEIR LOWER BRANCHES FOR MANY YEARS. THE BREAK IN THIS ROW SHOWS WHERE A SMALL TORNADO PASSED THROUGH IT.

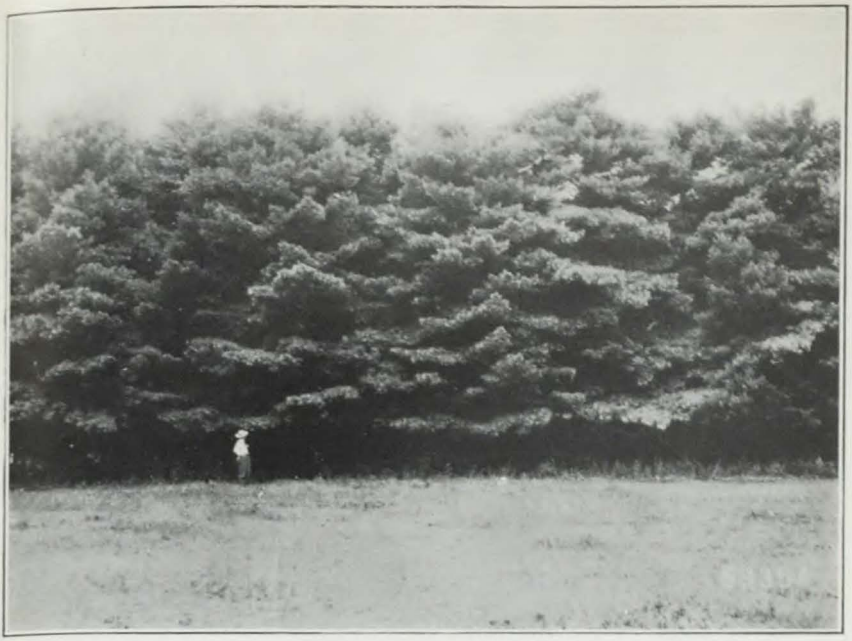

FIG. 1.—THIS YOUNG WHITE PINE GROVE IS DENSE AND THRIFTY, AND BRANCHY ENOUGH TO FORM A GOOD WINDBREAK.

FIG. 2.—THE ADDITION OF A FEW ROWS OF WHITE CEDAR ON THE OUTSIDE OF THE BELT REENFORCES THE BASE OF THE WINDBREAK.

(*b*) On the uplands and poorer situations of the Middle West, two classes of windbreaks are recommended; they may well be used on different parts of the same farm. The osage-orange hedge will serve in the driest situations, because of its drought resistance. Its sphere of influence can not be very wide; nevertheless, it will probably be inadvisable to have these windbreaks at more frequent intervals than 40 rods. Four osage-orange hedges, 25 feet high, will greatly reduce the general wind velocities on a quarter section and will give efficient protection to a large proportion of it. The windbreaks should, of course, extend from east to west across the farm. The post material should be cut before the end of 25 years, except on very dry situations, where it will require more time to grow first-class posts. It will be preferable to remove the larger trees from time to time rather than to destroy the hedge. If the hedges are to be cut to the ground, only one of the three or four on a farm should be taken in a single year.

While the osage hedge will furnish all of the posts needed, it will be best in most cases to have one wide belt of trees more nearly of a forest character. Green ash, honey locust, and Scotch and Austrian pines will produce a much larger volume of wood than can be obtained from osage orange. On situations not too dry, honey locust may profitably be planted in belts 44 feet wide if retained to the age of 30 years. Green ash has about the same capacity for height growth and furnishes more protection. Neither of these species alone makes an efficient windbreak; they should be supplemented with conifers. About eight rows of these hardwoods, 4 feet apart, should be planted at the outset, to be supplemented in a few years with three rows of Austrian pine on the north side. Scotch pine grows equally well, but on medium situations where severely exposed it will not make good form and will be fit only for fuel.

A belt of this sort should be so located as to protect the house, barn, and orchard from north winds. Because of its narrowness, all of the snow which it checks will not be deposited within the belt, so it should not be located too close to the north side of buildings or roads.

2. THE NORTHERN PRAIRIES.

(*a*) Primarily, in all of the northern prairie region the protection is needed against cold and dry winter winds and, secondarily, against the occasionally dry westerly winds of summer. The warm chinook, occurring in early spring, may also have very damaging consequences. To meet all of these, windbreaks of both orientations must be used, with about two of the north-south to one east-west. On good situations many conifers will succeed, about the most desirable being, in the order of their desirability, Scotch pine, red or Norway pine, Colorado blue spruce, and Black Hills spruce. Scotch pine develops well only when planted closely.

For Scotch and red pines, the maximum width of a belt, if the trees may be kept to the age of 40 years, should be about 75 feet. About 12 rows of the pines, 4 feet apart, should form the basis of the windbreak, these to be supplemented after about 15 years, when the trees will begin to prune themselves, with three rows of blue or Black Hills spruce on either side. There should be one such belt along the north border of every 160-acre farm, another along the west border, and two extending from north to south, at intervals of 60 rods from the west side. This will mean about 36 acres of timber for the farm, will not reduce the total productivity in crops, and will yield at the end of the rotation a large amount of material suitable for box boards, or at least for fuel.

(*b*) For Class B or poorer situations, very hardy species must be selected. Of these, western yellow and Scotch pines deserve most consideration for the basis of the windbreak, to be supplemented with blue and Black Hills spruces. The same arrangement should be made as on better situations, but on account of the slower height growth, the belts may not be so wide as before. A total width of 60 feet should not be exceeded, and an additional north-south row will be of value to the farm.

3. THE LAKE STATES.

(*a*) On almost any situation in the Lake States region, unless the soil be extremely poor and dry, white pine is preeminently the tree for windbreaks. It should be planted only in belts extending from north to south. The prevailing and damaging winds of this section are from the west, both winter and summer.

White pine grows rapidly enough so that it may well be planted in belts from 80 to 90 feet wide if it may be held for 40 years, or even greater widths if it is held to the age of 50. Even though the protective value is not so great as in more southerly regions, the increased quality of the products will warrant these wide belts. White pine should be grown for high-quality products, which will have an immense value. Close spacing, about 4 by 6 feet at the outset, is conducive to good form and rapid height growth.

A few rows of white cedar on either side will augment the value of the white pine windbreak, and will yield a crop of very valuable fence posts. The white cedar may be planted very closely—about 2 by 4 feet. Because of its slow growth, it should be planted simultaneously with the pine.

Orchard protection is generally more important than field-crop protection in the Lake States. Two north-south belts on a 160-acre farm will greatly modify the effects of dry westerly winds. The orchard should be adjacent to one of these belts and, as an additional precaution, should be surrounded by a double row of white cedar, spaced about 4 by 4 feet, with the trees in one row opposite the

middle of the space in the other. White cedar is a very efficient low windbreak, and is also very inoffensive in relation to crops, both as regards shading and sapping.

(*b*) On very poor, sandy soils, red and Scotch pines may be used in belts of the character described for Class B situations on the northern prairies. The spruces may be supplanted by jack pine as an auxiliary, but this species should be used sparingly, as it is extremely aggressive in competition with other forest trees on raw soils.

4. THE EASTERN STATES.

In the northern portion of this region, where the winter winds chiefly are to be feared, white pine may be as fully recommended as in the Lake States. The native white spruce, Norway spruce, or white cedar may be used with equal advantage as an auxiliary, but, in small quantities. The last will probably find the most ready market, since the spruces will be valuable only for pulpwood. A double row of Norway spruce forms an excellent windbreak when timber values are not to be considered. The ideal spacing seems to be about 8 by 8 feet. The north-south windbreak will here act as a barrier to nearly every wind, since all are of westerly origin.

Toward the south in this region, where, because of the greater summer heat the conservation of moisture becomes more important, chestnut and tulip poplar may be recommended as the most profitable hardwoods, and may be used even on rather barren or worn-out soils. Both grow thriftily and may be managed as coppice. As an auxiliary, short-leaf pine may be suggested for use on soils too poor for white spruce or white cedar. The common red cedar, which is such an important feature of natural hedgerows, should not be allowed to exist in the neighborhood of apple or pear orchards.

5. THE SOUTHWEST.

Very little windbreak planting has been done in the poorly watered region of the southwestern United States, although it is evident that here, of all places, protection from wind and conservation of moisture are most needed.

Artemisia or sagebrush has been used to some extent in New Mexico. Because of the low height attained by these shrubby species, the hedges must be very close. With a height of 4 feet, hedges should be placed at intervals of from 80 to 100 feet. The east-west orientation will best obstruct the continental winds blowing off the Gulf and the anticyclonic winds, usually from a southwesterly source.

Although osage orange is native only to the river bottoms of this region, it is believed that with the encouragement of cultivation this species could be made to grow in much of the territory where dry farming is practiced.

Of species suitable for furnishing winter protection only the alligator juniper and the piñon are sufficiently drought resistant to live in the climate of the lower elevations.

6. THE PACIFIC COAST.

In California windbreaks have been principally used by fruit growers for the protection of very valuable citrus orchards. There can be no doubt as to the value of eucalypts, Monterey cypress, and Monterey pine for this purpose, especially when located along the north side of an orchard, to check the spring winds.

Hardly less important in southern California is the protection of all kinds of farm crops from the "Santa Ana" or dry north wind which occasionally blows out of the mountains. It has entirely destroyed a wheat crop in a day or two. The one thing that counts against certain profit in the immense wheat fields of California is the very fact of their unbroken immensity. There seems to be no good reason why the development of eucalypt planting in California should not also aim toward a thorough protective system for those fields, for which east-west belts of moderate width are recommended. Eucalypts grow rapidly and will for a number of years form a very dense windbreak. Underplanting will not be found practicable.

In Washington and Oregon winds blowing out of the mountains are hardly less severe than the California "Santa Ana" in their effects upon field crops and orchards. The protection of orchards against winds carrying sand is, in the Columbia River Valley, to be obtained by the use of poplars and willows, while the more extensive shelters for grain fields may well consist of belts of Carolina poplar or cottonwood, to be handled under the same system as has been recommended for the river bottoms of the Middle West.

As a final word, it must be concluded that the right kind of a windbreak in the right place is a source of profit and of comfort; on the treeless plains of the Middle West it has no little esthetic value. What prejudice exists against its use is based on two things: First, experience with poorly-planned and poorly-planted windbreaks; second, a lack of appreciation of the protection and profit which a windbreak affords.

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